

STUDIES OF IDENTIFIED PARTICLES PRODUCED IN HIGH
ENERGY PP COLLISIONS WITH A HIGH p_T TRIGGER

BY
ALF NILSSON



LUND 1983

STUDIES OF IDENTIFIED PARTICLES PRODUCED IN HIGH
ENERGY PP COLLISIONS WITH A HIGH p_T TRIGGER

Bye due permission of the faculty of mathematics
and natural sciences of the University of Lund to
be publicly discussed at the lecture hall B of the
Department of Physics, December 8, 1983, at 10.15 a.m.,
for the degree of doctor of philosophy

BY

ALF NILSSON
Fil.kand.
Lund 1983

Organization LUND UNIVERSITY	Document name DOCTORAL DISSERTATION	
	Date of issue	
	CODEN: LUNFD6/ (NFFL-7019)/1-108/1983	
Author(s) Alf Nilsson	Sponsoring organization	
Title and subtitle Studies of identified particles produced in high-energy pp collisions with a high p_T trigger		
Abstract Studies in experimental high energy physics. Construction and application of an aerogel Cerenkov counter for particle-identification. Investigation of identified particles produced in high energy proton-proton collisions characterized by a particle with large transverse momentum. Studies of charge - and flavour correlations between the large transverse momentum particle and its associated particles. Comparisons with the Lund-model for pp collisions. The experiment was performed at the intersecting storage rings (ISR) at CERN using the axial field spectrometer (AFS). The results are generally explainable using a simple parton model.		
Key words Experimental high energy physics. Aerogel Cerenkov detector. Proton-proton collisions. High-PT. Correlations. Identified particles.		
Classification system and/or index terms (if any)		
Supplementary bibliographical information		Language English
ISSN and key title		ISBN
Recipient's notes	Number of pages 108	Price
	Security classification	
Distribution by (name and address)		

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature Alf Nilsson

Date 5 october 1983

enl SIS 61 41 21

THESIS

Studies of identified particles produced in high
energy pp collisions with a high pT trigger.

Alf Nilsson
Elementary Particle Physics
Department of Physics
University of Lund
Lund

This thesis is based on the following four papers:

1. The Axial Field Spectrometer at the CERN ISR.
H. Gordon et al, Nucl. Instr. and Methods 196(1982) 303-313

2. An Aerogel Counter for the AFS Experiment.
S. Henning et al, Physica Scripta Vol 23, 703-707, 1981.

3. Performance of an Aerogel Cerenkov Counter using
wavelength shifter readout.
A. Nilsson, LUNFD6/(NFFL-7003)/1-19/(1981).

4. Ratios of inclusive particle production at high
transverse momentum and correlations between an identified
charged particle at high transverse momentum and identified
associated charged particles in pp collisions at c.m.s energy
of 63 GeV.

B. Lörstad, A. Nilsson University of Lund Lund
G. Damgaard, Niels Bohr Institute Copenhagen
LUNFD6/(NFFL-7018)/1-27(1983)

I have participated in a high energy physics experiment
that have produced a number of results on several topics. My
contributions have mainly been concentrated to the subjects
presented in this thesis



1 Introduction

The idea of hadrons being composite objects has evolved gradually over the past twenty years and today there is a rather successful theory of quarks and gluons called the Quantum Chromo Dynamics (QCD).

To describe the growing number of hadronic states (the "Particle Zoo") being discovered during the fifties and the sixties, Gell Mann and Zweig (1964) presented the quark model (QM) with three fundamental constituents or building blocks which they called quarks. These were given fractional electric charges and other quantum numbers such that if combined according to a simple prescription one was able to construct all hadrons known at that time and even to predict new ones: the experimental verification of the Omega minus (1964) was a great success for the QM. According to the QM prescription only two different ways of combining quarks into hadrons are necessary: three quarks make up one baryon, a quark and an anti-quark make up one meson. Later new hadronic states have been discovered which makes it necessary to extend the species of quarks from three to five and a sixth one is proposed.

In the late sixties lepton-hadron scattering at SLAC showed evidence for pointlike constituents inside the nucleon (Panofsky 1968) and in the decade to follow measurements of structure functions gave further support of the QM. In scattering experiments hadron constituents were usually referred to as partons (Feynman 1967) and the word quark was used when describing static properties of hadrons (Spectroscopy). Lepton-hadron scattering only probes the charged partons. Structure functions are built from momentum distributions of all charged partons inside hadrons and it was necessary to add to the basic quarks, called valence quarks, a background of quark anti-quark pairs, which was given the name sea quarks. From relations between structure functions the fraction of hadron momentum carried by electrically charged partons can be determined and experiments found a value about one half. Thus electrically neutral partons must exist that carry the other half the momentum.

In order to explain a number of experimental facts the invention of a new quantum number with three degrees of freedom, given the name color, has proved very successful. Such experimental facts are e.g. the ratio of hadrons to muon pairs produced in e^+e^- collisions, the life time of the neutral pion and the existence of the Δ^{++} resonance.

The concept of color is the key to the theory of strong interactions, Quantum Chromo Dynamics (QCD). In QCD the strong color force is mediated by electrically neutral partons called gluons. The gluons are assumed to be the electrically neutral constituents that carry the missing momentum found in lepton-hadron scattering. They are also believed to be the source of the sea of quark anti-quark pairs through vacuum polarization by the gluons. QCD was successfully explaining (1980) the scaling violations observed in large momentum transfer lepton-hadron scattering since around 1975. The discovery of three jet events at PETRA (1980) and e.g. the rate of single photons at the ISR further supports QCD.

Another experimental fact so far is the nonobservation of

free quarks and gluons: only complete hadrons are observed. In QCD the color force acting between colored constituents decreases with decreasing distance (Asymptotic freedom). On the other hand as the distance increases so does the color force tending to confine partons within a small volume (Quark confinement). By some yet unexplained mechanism only color neutral or white hadronic states are believed to exist.

When two quarks collide in a hadron-hadron collision with large momentum transfer, ie. at a small distance from each other, they are scattered as free and unbound by the color force. On the other hand, as they move apart the action of the color force increases and the net result is a production of hadrons. By a mechanism called fragmentation quark anti-quark pairs are created in the color forcefield and these combine with each other and with the scattered quark(s) to form color neutral hadrons.

One signature of quark scattering is the change of shape in the single particle cross section with p_T from an exponential to a power dependence, at p_T around 1 GeV/c, indicating the change of scale from hadron-hadron to parton-parton scattering. The occurrence of a single high p_T particle is however rare.

In order to study the effects from hard scattering of partons in hadron-hadron collisions and the effects of fragmentation one thus needs a detector which can select high p_T particles that are believed to contain a scattered quark or a quark from the fragmentation of a gluon in the case of quark-gluon scattering. To study the general effects of fragmentation one needs to register and identify the associated particles close to the high p_T particle in the central region (the trigger jet). The particles appearing on the away side of the high p_T particle (the away jet) can give information on the nature of the hard scattering and should be registered and identified as well.

2 The Axial Field Spectrometer

The Axial Field Spectrometer (AFS) was designed to study large transverse momenta particles (high p_T) and large transverse energy flow (high ET) in the central region together with the associated particles in the central region. The AFS is installed at the CERN Intersecting Storage Rings (ISR).

2.1 The ISR

In the ISR beams of charged particles, usually protons, are stored, circulating in two separate beam tubes of ultra high vacuum (less than 10^{-12} Torr). The beam tubes cross at eight intersection regions where the experimental detectors are set up. The two beams circulate in opposite directions and collide almost head on at the intersections to maximize Center of Mass energy (CM energy). The beams are debunched and fill the whole circumference of the ISR to collide continuously at a typical rate of 0.8 MHz. The particles are injected from the Proton Synchrotron (PS) where they are accelerated up to 26 GeV/c and can be further accelerated in the ISR, up to about 31.5 GeV/c. The maximum available CM energy is 63 GeV.

Particles used in the ISR are, besides protons, antiprotons, deuterons and alpha particles. The beams can be stored for several days.

2.2 AFS. Introduction

The central part of AFS (paper 1) consists of a 1.4 m long cylindrical Drift Chamber (DC) situated between the pools of the Open Axial Field Magnet. The magnetic field of 0.5 Tesla is parallel to the DC wires. Inside the DC, surrounding the beam tubes, there is an inner "barrel" hodoscope (IH). The IH is used as pretrigger and for event time determination. Along the downstream beams there are hodoscopes used for luminosity measurements and also serving as another pretrigger.

Several additional detectors are placed outside the DC. At the start there was a liquid argon calorimeter on one side and an arm of Cerenkov counters and Multi Wire Proportional Chambers opposing it. Later the liquid argon calorimeter was replaced by a wall of Uranium calorimeters and after some time also roof and floor calorimeters (on top and below the central detector) were installed. Finally calorimeter stacks have replaced the Cerenkov arm as well. (See Fig. 2.1).

In this thesis we make use of the central detector and the Cerenkov arm.

2.3 The Central Detector

The IH consists of 44 8° scintillator strips ~ 1 m long parallel to the beams. It is surrounded by the cylindrical DC. The DC is 1.4 m long and extends radially from 0.2 to 0.8 m. It is segmented azimuthally into 88 4° sectors. Each sector has 42 sense wires radially. These are staggered to resolve the left-right ambiguity of tracks. Signals from ionizing tracks passing through the DC are collected and amplified at both ends of a sense wire and sent to a shaper and ADC (Analog to Digital Converter) in the Control room. This information is used to determine the coordinate along the wire of the passing track and to measure the ionization loss, dE/dx , for particle identification at low momenta. A fast signal is also sent to a Drift Time Recorder (DTR). Because the drift velocity of the electrons from the ionization is known the DTR time tells the distance a track has passed from a wire. Only ADC's connected to a wire with DTR signal are read by the online computer and stored onto magnetic tape for further analysis.

The offline analysis of the DC information proceeds in two steps. First a geometrical pattern recognition program (INGER) finds the tracks and passes this information to the second step of momentum determination in another program (MARTHA). In MARTHA the dE/dx information is used for particle identification.

2.4 The outer detector. The Cerenkov Arm

The Cerenkov arm is situated at 90° to the intersection, covering 90° in polar angle and 48° in azimuth (0.8 sr). It consists of three threshold Cerenkov Counters, Aerogel (AGC), High Pressure (HPC) and Atmospheric (AC) Cerenkov Counters with gamma thresholds of 3, 10 and 20 respectively. Between the AGC and the HPC and between the HPC and the AC are placed two sets of Multi wire proportional chambers, PC1 and PC2.

2.5 High pT Trigger

Charged particles are selected with thresholds up to 5 GeV/c in the Cerenkov arm. The trigger proceeds in the following three steps. (Quoted rates correspond to a luminosity of $2 \times 10^{31} (\text{cm}^2 \text{s})^{-1}$ giving the IH a rate of 0.6 MHz).

1. Single Particle Trigger (SPT), consists of a coincidence between each of the six IH strips facing the Cerenkov arm with a second coincidence between groups of wires in PC1 and PC2. The SPT rate is typically 60 kHz (rejection factor 10) with a decision time of 60 ns . The SPT threshold is 800 MeV/c .

2. A Random Access Memory (RAM) matrix box, pretriggered by the SPT, compares hits in individual wires in PC1 and PC2. The rate after RAM is 10 kHz (rejection factor 6) at highest threshold with a decision time of 700 ns .

3. The ESOP micro programmable processor calculates a rough momentum of tracks selected by RAM. It uses DTR information from the DC sectors pointed at by RAM. The ESOP rate is a few Hz with a decision time of $200 - 300 \text{ micro seconds}$ and an event rejection of about 2000 at the highest threshold 5 GeV/c .

The high pT triggers are analysed offline in a third program (CARMEN). With trigger threshold at 5 GeV/c about 10% of the events survive. False triggers are mainly of two kinds: 1. One low momentum track simulating a high momentum track because of low momentum resolution at the ESOP level. 2. Two overlapping low momentum tracks simulating a high pT track.

The AFS detector is thus well suited to study and identify central charged high pT particles and their associated charged particles moving close in the same direction (trigger jet). As the polar angle of the away side jet varies from event to event its full detection is limited by the DC's central acceptance. Also the identification of the away side jet particles is limited to low momentum.

3 The Aerogel Cerenkov Counter for the Axial Field Spectrometer

3.1 Cerenkov Radiation

Cerenkov radiation (CR) is produced in a medium at the passage of an electrically charged particle moving with a velocity greater than the speed of light of the medium.

The first observation of CR was reported from P. and M. Curie who saw a bluish glow in their bottles of radium solutions. During the twenties Mallet found the CR spectrum to be continuous and even managed to photograph it. The following decade Cerenkov and Vavilov studied CR in deeper detail and performed a number of experiments on it. Cerenkov found e.g. that CR is sent out only at a certain angle with respect to the path of the particle producing it. The classical explanation of CR was presented the same decade by Frank and Tamm, according to which the CR is produced by a electrically charged particle traversing the medium with a velocity β greater than the velocity of light in that medium c_m

$$\beta > c_m = 1/n \quad (a)$$

where n is the refractive index of the medium. (The velocity of light in vacuum and Planck's constant are set to 1 throughout.) The passage of a charged particle through the medium polarizes it and when the velocity β fulfills (a) a coherent electromagnetic wave front is emitted, the CR. The emission angle θ depends the velocity β

$$\cos \theta = 1/\beta n \quad (b)$$

1940 Ginsburg presented the quantum mechanical theory for CR.

In the classical theory of Frank and Tamm the average number of Cerenkov photons dN emitted per unit photon energy interval dE , for a radiator of thickness L , is given by

$$dN/dE = 2\pi \alpha L Z^2 \sin \theta \quad (c)$$

where α is the fine structure constant and Z the number charge of the traversing particle. Integrating over the continuous CR spectra between wavelengths λ_1 and λ_2 gives the number of CR photons, N

$$N = 2\pi \alpha L Z^2 (1/\lambda_1 - 1/\lambda_2) (1 - 1/(\beta n)^2) \quad (d)$$

where we used (b) and (c).

3.2 Cerenkov Detectors. General

Cerenkov counters (CC) consist of three main parts: radiator, light collecting system and photo sensitive devices, such as PM's (Photo Multiplier tubes).

Radiators suitable for particle physics have refractive indices n between 1 and 2, see table 1. Gaseous detectors have

been used most widely because n is changed easily by changing the gas pressure. For n in the region 1.02 to 1.1 the only available radiators were cold liquids and gases under very high pressure (25 bar) but these need thick container walls that absorb, scatter and create particles. The innovation of aerogel fills this gap nicely. Aerogel is easier to manage because it is solid and needs no special container.

Table 1			
Some Cerenkov radiator materials			
$[\gamma_{th} = 1/(1 - \beta_{th}^2)^{1/2}]$			
Radiator	n (visible light)	Threshold (γ_{th})	
Plexiglas	1.50	1.4	
Liquid H ₂	1.11	2.4	
Liquid He	1.02	5.0	
Aerogel	1.02 - 1.06	3.0 - 5.0	
Freon (at STP)	1.0017	17	
He (at STP)	1.000033	123	

Measuring the emission angle θ , together with a knowledge of n determines the velocity β of the particle (eq b). Knowing the momentum p the mass m can be obtained from

$$p = m\gamma\beta \quad (e)$$

The most common application is when the CR is collected without knowledge of the angle θ . These Cerenkov Counters are called Threshold Cerenkov Counters (TCC). When θ is determined one speaks of differential or focusing CC. TCC thus detects particles moving with a momentum p

$$p > p_{th} = m(\gamma\beta)_{th} = m/(n^2 - 1)^{1/2} \quad (f)$$

Usually one wants to identify the most common hadrons i.e. π , K and p . As the masses of these three particles are known, measurement of momentum using magnetic deflection and a sequence of CC with different thresholds will provide the particle identification. An example of such a CC system is the Cerenkov arm in the AFS, see Fig. 2.1.

The efficiency of a CC is determined by the number N^- of Cerenkov photons detected

$$eff = 1 - \exp(-N^-) \quad (g)$$

A major detector task is to collect as many photons as possible. The number of photons detected N^- is usually well described by

$$N^- = A (1 - 1/n^2 \cdot (1 + 1/(m/p)^2)) \quad (h)$$

for $p > p_{th}$. A is a constant depending on the detector efficiency. The photons are transported from the radiator to the photo sensitive devices in a light collecting system. This consists usually of a system of highly reflective mirrors and focusing cones.

An interesting development of differential CC are the ring-imaging CC. Here the light cone is focused into a ring image onto a photosensitive proportional chamber using spherical mirrors.

3.3.1 The Aerogel Cerenkov Counter (AGC)

Papers 2 and 3 describe the features of the AGC. The aerogel is a solid but very light and fragile medium consisting of silicon-dioxide and air. It is rather transparent to visible light and somewhat bluish. The refractive index can be varied between 1.02 and 1.06, depending on production factors. The micro structure of aerogel is small grains, around 100 nm in diameter.

The operation at ISR was limited because of lack of space and forced a construction of very dense cells with light collection through Wavelength shifters (WLS) behind the aerogel. Coupled to the WLS were bars of plexiglass several meters long (with a number of joints) transmitting light to PM:s behind an iron shield. This reduced the efficiency so that the aerogel CC could be used only in the signal mode, i.e. above threshold. See Fig. 3.1 for a general view of the detector construction.

The AGC efficiency determined in the analysis of paper 4 was found to be somewhat lower than found earlier, see below. This is partly due to accumulation of water vapour in the aerogel. The mean single cell efficiency was 0.23 at $\beta \sim 1$ with a noise background of 0.07. The background was found from cells not hit in an event. We used pions identified by the HPC to determine the efficiency.

A possible improvement of a similar CC would be to use vacuum photodiodes which can operate in a magnetic environment thus eliminating the need for long light guides.

3.3.2 Aerogel Cerenkov Counter operation

In the analysis of paper 4 the Aerogel Cerenkov Counter (AGC) and the two gaseous Cerenkov counters (HPC and AC) were used for particle identification in addition to the dE/dx measurement in the drift chamber.

For particles with momentum in the range from about 0.5 GeV/c to about 2 GeV/c the AGC is the only operating detector for pion identification. Also in the momentum range from around 2 GeV/c to around 5 GeV/c where identification in the two gaseous Cerenkov counters cannot separate K from p the AGC can be used to select kaons in the range from 2 GeV/c up to about 3.5 GeV/c.

The noise in the AGC cells is mainly contained within a few ADC channels but with long tails reaching into the pulse-height region where the aerogel Cerenkov signals appear. Thus some of the noise cannot be eliminated and we found the level of 7% at a convenient choice of discrimination level.

Signals from tracks passing through the WLS are much larger than the Cerenkov signals. The distance of the AGC from the intersection region and its vertical position was determined with these pulses. Fig. 3.2 show pulses larger than 2 photoelectrons plotted versus the distance from the WLS in a single cell. Signals from tracks hitting the WLS is clearly seen. To eliminate such hits in the analysis we put an upper cut of 4 photoelectrons. Thus signals with pulses larger than the noise level and less than 4 photoelectrons are accepted.

Fig. 3.3 shows the mean single cell efficiency versus momentum in the AGC for pions. With single efficiency we mean the fraction of the tracks passing through a particular cell that give a signal in that cell larger than the noise level of that cell. Pions were identified by dE/dx for momenta below 0.5 GeV/c and by the gaseous Cerenkov counters for momenta above 2 GeV/c. We see the noise level of 7% below the AGC threshold at 0.5 GeV/c and a reasonably constant efficiency at momenta above 2 GeV/c. Fig. 3.4 shows the aerogel single cell efficiency for all tracks where the threshold around 0.5 GeV/c is clearly seen with a following steep rise in the efficiency. At higher momenta there is a slow rise with small "jumps" at about 2 GeV/c and 3.5 GeV/c (above the kaon and proton thresholds, 1.5 GeV/c and 3 GeV/c respectively).

A track through the AGC passes in the mean 3.5 cells. The efficiency of the whole AGC requiring at least one signal vs momentum for tracks identified by dE/dx and by the gaseous Cerenkov counters is shown for pions in Fig. 3.5 and for heavier particles in Fig. 3.6. There is a gap for pions in the region where these counters give no pion identification. The points for heavier particles rises just above the kaon threshold and there is a second rise above the proton threshold. Similar plots for kaons and protons separately show the same efficiency as for pions at momenta well above their respective thresholds. The AGC has an efficiency of $59.6\% \pm 0.4\%$ for a $\beta \sim 1$ particle with a background of $22.1\% \pm 0.4\%$.

Requiring two cells with signals increases the signal to background ratio. For particles identified in the two gaseous Cerenkov counters we find a mean efficiency of $20.3\% \pm 0.2\%$ with a background of $3.3\% \pm 0.1\%$. The signal to background thus increases with a factor of 2 but the number of particles being identified also goes down a factor 2.

4 Correlations with a high pT particle in pp collisions

In paper 4 is investigated how the charge of an identified charged high pT particle is compensated by other identified charged particles in the event. This paper presents also ratios of charged identified particles to all charged particles at high pT. However I have been mainly concerned with the studies of the two-particle correlations.

The high p_T experiment was performed in pp collisions at a CM energy of 63 GeV using the AFS detector at the ISR. The selection of the high p_T particles was done by the ESOP trigger. Particle identification at low momenta was done using the DC dE/dx information and at higher momenta, for particles moving inside the acceptance of the Cerenkov arm, by the Cerenkov counters. Only triggers with p_T greater than 3 GeV/c were used in the charge correlation studies to make sure (or more probable) that we really probe particles containing a leading quark from the hard scattering between the proton constituents. The associated particles in the event were required to have a p_T of at least 0.3 GeV/c to avoid particles belonging to the beam jets.

A number of cuts on the tracks to select only those which are reasonable well measured was used in the analysis, see paper 4. After all cuts on the tracks an event contains in the mean 4 tracks plus the trigger particle and 1 out of these goes into the Cerenkov arm.

The most important results found in paper 4 are the following: The charge of the fastest particle in the trigger side jet is strongly compensated in the hemisphere containing the fast particle. Furthermore, the charge compensation is seen to depend on the identity of both the fastest and of the associated particle. The strongest compensation is of heavy fast particles by heavy associated particles.

On the away side positively charged associated particles are in majority in general, reflecting the excess of u-valence quarks in the event. The ratio of positive to negative away side particles increases with p_T of the associated particle, the ratio with positive triggers being lower than the ratio with negative triggers. For triggers containing a proton valence quark (pions and positive heavies) the number of positive and negative particles is, at their highest p_T , the same within error bars. This is an indication of flavour independent hard quark-quark scattering.

In the case of heavy triggers, however, we find a larger excess of positive over negative high p_T away side particles for negatively than for positively charged triggers. This effect is not expected in QCD where scattering between partons is flavour independent because gluons carry no flavour and no charge. One difference between pions and heavy negative triggers is that one of the quarks in the pion can be one of the proton valence quarks (the other coming from the fragmentation) as can be the case also for positive heavy particles. A heavy negative particle contains none of the proton valence quarks.

Finally we found no difference between the ratio of positive to negative away side particles for different angles between the trigger particle and the fastest away side particle.

5 Conclusions

" No victory without sacrifices"
T. Dahmén

My efforts in high energy physics have mainly resulted in the following subjects: First of all I have had the major responsibility of the construction and testing of an Aerogel Cerenkov Counter installed in the AFS detector at the CERN ISR. I have used this counter for particle identification in my second principal commitment: the studies of particle correlations with a high p_T trigger particle. These showed interesting effects, in general explainable using a simple parton picture but also one effect neither understood in that language nor in that of QCD.

Acknowledgements

First of all I want to thank all those constituting the high energy physics groups at Lund for producing a stimulating atmosphere at my home institute. I am specially grateful to G. Jarlskog for valuable guidance at the construction and operation of the Aerogel Cerenkov Counter and to B. Lörstad for our collaboration concerning the two-particle correlation studies.

Finally I wish to express my gratitude to all the members of the Axial Field Spectrometer collaboration.

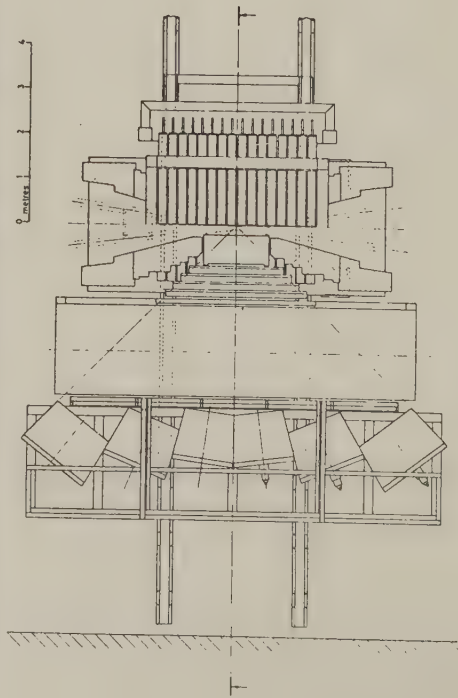
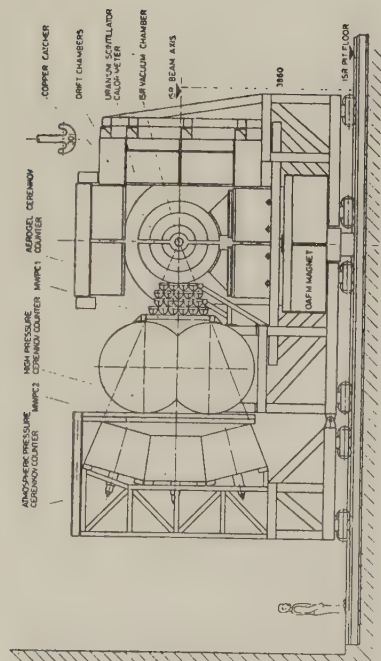
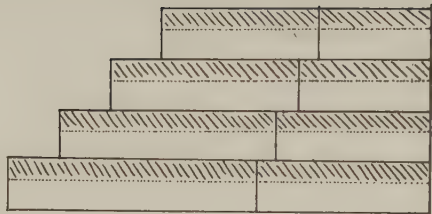
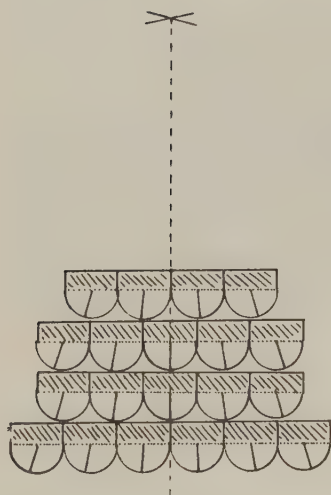


Fig 2.1



(a) Vertical cut through the aerogel detector at the polar angle 90° . The height of each cell is 20 cm. (b) Horizontal cut showing one half on the aerogel detector (compare with Fig. 2.1)

Fig 3.1

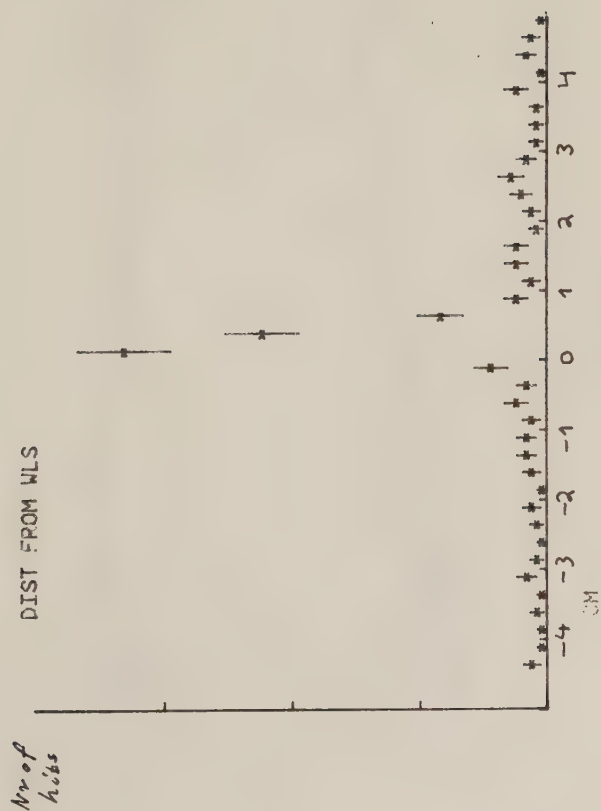


Fig 3.2

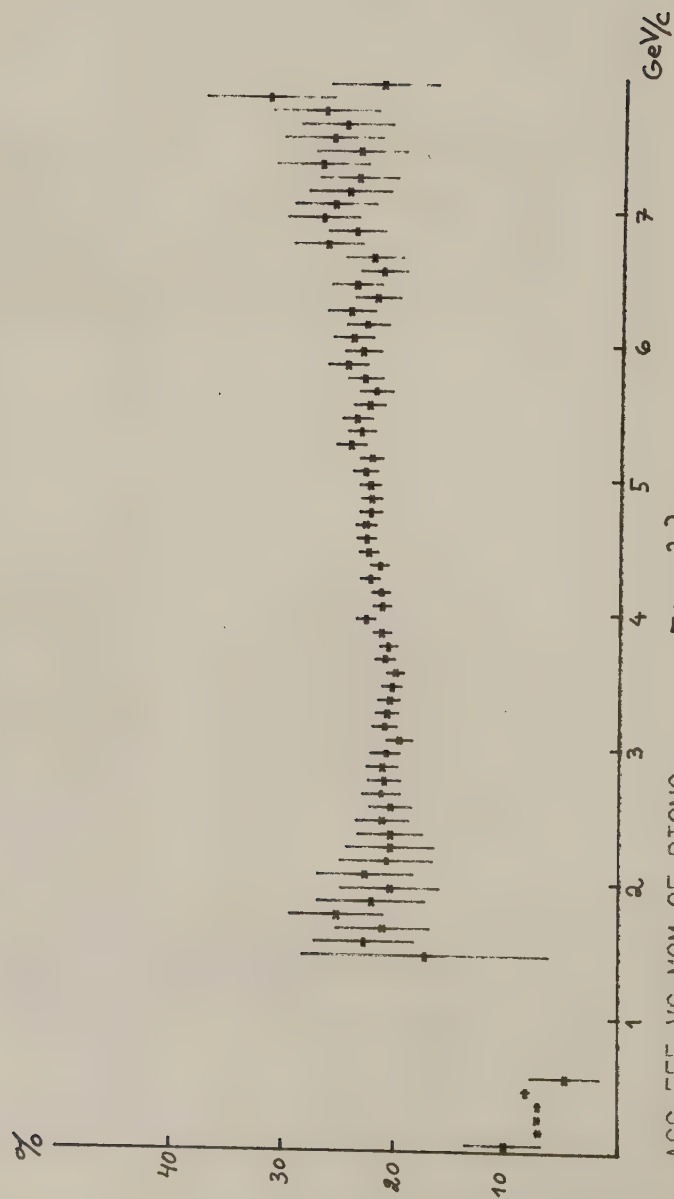


Fig. 3.3

AGC-EFF VS MOM OF PIONS

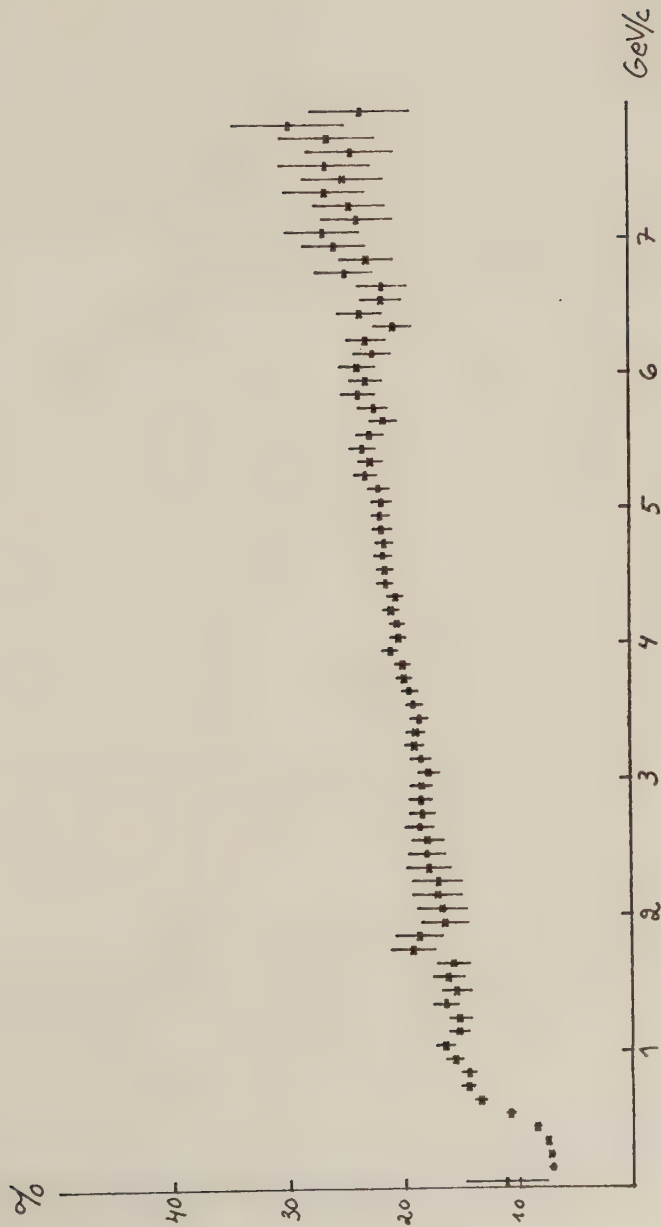


Fig 3.4

AGC EFF VS MOM ALL TRACKS

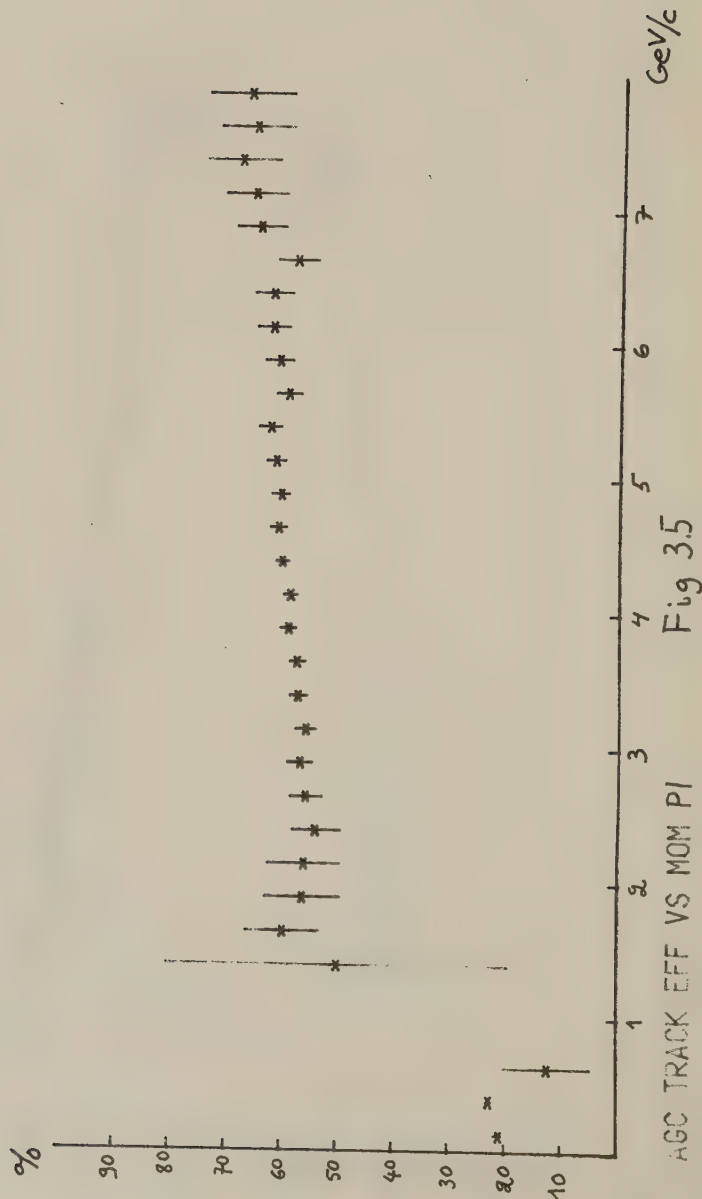


Fig 3.5

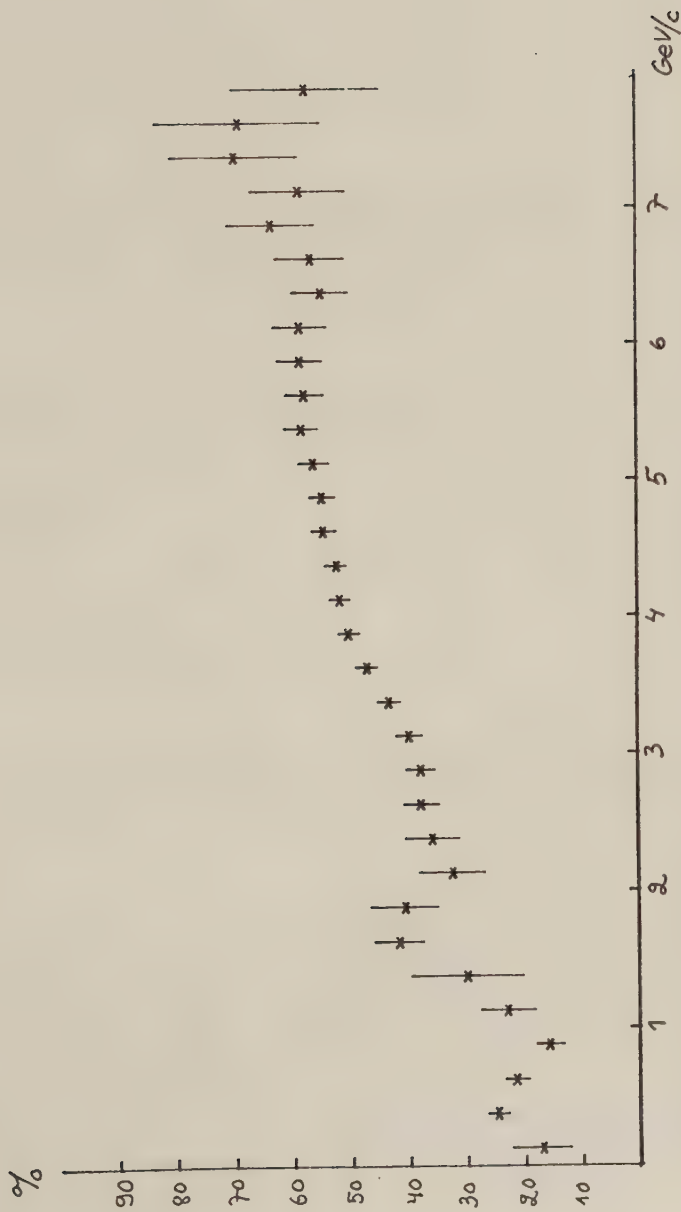


Fig 3.6

AGC TR EFF VS MOM HE

THE AXIAL FIELD SPECTROMETER AT THE CERN ISR

Brookhaven–CERN–Copenhagen–Lund–Rutherford–Tel Aviv Collaboration

H. GORDON, R. HOGUE, T. KILLIAN, T. LUDLAM, M. WINIK, C. WOODY

Brookhaven National Laboratory, Upton, New York, U.S.A.

D. BURCKHART, V. BURKERT, O. BOTNER, D. COCKERILL, W.M. EVANS,
C.W. FABJAN, T. FERBEL, P. FRANDSEN, A. HALLGREN, B. HECK, M. HARRIS,
J.H. HILKE, H. HOFMANN, P. JEFFREYS, G. KANTARDJIAN, G. KESSELER,
J. LINDSAY, H.J. LUBATTI, W. MOLZON, B.S. NIELSEN, P. QUÉRU,
L. ROSSELET, E. ROSSO, A. RUDGE, R.H. SCHINDLER, T. TAYLOR,
J. v.d. LANS, D.W. WANG, Ch. WANG, W.J. WILLIS, W. WITZELING

CERN, European Organization for Nuclear Research, Geneva, Switzerland

H. BØGGILD, E. DAHL-JENSEN, I. DAHL-JENSEN, Ph. DAM, G. DAMGAARD,
K.H. HANSEN, J. HOOPER, R. MØLLER, S.Ø. NIELSEN, L.H. OLSEN, B. SCHISTAD

Niels Bohr Institute, Copenhagen, Denmark

T. AKESSON, S. ALMEHED, G. von DARDEL, G. JARLSKOG, B. LÖRSTAD, A. MELIN,
U. MJÖRNMARK, A. NILSSON

University of Lund, Lund, Sweden

M.G. ALBROW, N.A. McCUBBIN, M.D. GIBSON, J. HIDDLESTON

Rutherford Laboratory, Chilton, Didcot, England

O. BENARY, S. DAGAN, D. LISSAUER and Y. OREN

Tel Aviv University, Tel Aviv, Israel

The axial field spectrometer is being exploited in a wide-ranging programme to study pp and p $\bar{p}$ -collisions which are characterized by a large transverse momentum. A specially shaped magnet together with an "imaging" drift chamber is used for efficient detection and momentum analysis of high multiplicity events at interaction rates of up to 5×10^9 s. Particle identification is accomplished over 1 sr; an uranium/scintillator hadron calorimeter will cover more than 8 sr in 1982 to provide an unbiased energy measurement.

1. Introduction

The axial field spectrometer (AFS) was recently brought into operation at the CERN ISR. It is being exploited in a wide-ranging programme to study different aspects of those proton–proton or proton–antiproton collisions which are characterized by a large transverse momentum (P_T). Examples include the measurement of inclusive distributions of identified high- P_T hadrons, and the study of event structures characterized by a large transverse energy (E_T) or the production of one or several high- P_T electrons or photons.

Our experimental approach to this programme em-

phasizes integration of advanced magnetic spectroscopy with state-of-the-art calorimetry. These techniques are fully exploited to provide the maximum information on all particles produced. In addition, information from these detectors is used in new ways for on-line event triggering and filtering; this allows even very rare events to be selected with high efficiency, an essential prerequisite for studies at a high-luminosity hadron collider, such as the ISR.

We aimed at considerable modularity of the detectors. Apart from clear advantages of construction, running, and servicing of such components, modularity provides us with ease for addition or reconfiguration of

our system to emphasize the study of specific final states. At present, for example, a 1 sr Cherenkov detector system allows hadron identification up to $p \approx 12$ GeV/c; liquid-argon electromagnetic calorimeters and a uranium-scintillator calorimeter ("hexagon") are used for a study of events containing direct photons.

2. AFS components and their performance

The 1981 layout of the AFS is shown in figs. 1 and 2. Fig. 2 also shows the recently installed low- β insertion, comprising a total of eight superconducting quadrupoles. These are the first superconducting beam elements to be used in a storage ring; they are now operational with colliding beams, producing a sixfold increase in luminosity.

2.1. The open axial field magnet

The design [1] contrasts with earlier magnetic spectrometers for ISR physics [2]*:

- a) It is a warm magnet because:
 - a magnetic field integral of $0.5 \text{ T} \cdot \text{m}$ provides a momentum resolution of $\delta p/p = 0.01p$, which is satisfactory for our physics programme;
 - the low field level facilitates the operation of the drift chamber and minimizes effects on the ISR beams, which traverse the field at an angle of $\pm 7.5^\circ$;
 - it is easier and cheaper to construct and more reliable to operate;
 - it greatly facilitates the implementation of item (b);
- b) Its unique form (fig. 3) reflects our insistence on integrating the magnetic spectrometer with the surrounding detectors (calorimeters, Cherenkovs) by maximizing the totally unobstructed aperture for particle detection, even in the forward direction:

azimuthal coverage: $0 \leq \phi \leq 2\pi$,

polar coverage: $0 \leq \theta \leq 15^\circ$ and $40^\circ \leq \theta \leq 140^\circ$.

- c) It allows very rapid access (within 5 min) to the complex central detector; this is crucial for the ISR, which is operated continuously, except for very short (~ 2 h) interruptions that are several days apart. It allows access to the vacuum pipe in about one hour of time, if machine intervention (vacuum, etc.) becomes necessary.

The level and direction of the magnetic field is also shown in fig. 3.

Over the volume of the vertex detector the field is azimuthally symmetric to better than 0.5%; the field

integral transverse to the particle direction as a function of polar angle is shown in fig. 4; approximately constant momentum resolution is achieved for particles of a given P_T for polar angle in the range $45^\circ < \theta < 135^\circ$.

The magnet is operated routinely with either polarity, at a single nominal field level. The field component affecting the circulating beams is corrected using dipole compensator magnets on either side of the spectrometer; by raising and lowering the excitation currents simultaneously it is possible to turn the magnet on and off with stored beams, a feature which is used for checks. The total power consumption of the magnet system is 700 kW.

2.2. The vertex detector

For completeness we summarize the salient features and refer for more details to an extended discussion given elsewhere [3]. The physics programme and the high-interaction rate environment dictated the design considerations. In particular, the detector was optimized for efficient registration and analysis of final states with high multiplicity and high particle density ("jets") [4]. This is accomplished by highly redundant non-projective track-point measurements. The azimuthal coordinate perpendicular to the magnetic field is measured using drift techniques, whereas the coordinate along the drift wire is obtained with the charge-division method [5]. The 140 cm long cylindrical chamber (inner active radius 21 cm, outer active radius 80 cm) is organized in 4° sectors, with 100 μm Cu-Be wires serving as the sector-separating cathodes. Along the radius of such a sector a total of 42 drift wires (30 μm diameter) measure the track position.

The performance, obtained in high luminosity ISR running (interaction rate $\gtrsim 800$ kHz), is at present found to be:

σ (drift) = 200 μm ,

σ (charge division) = 1.5 cm (at a gas gain of about 2×10^4),

$\sigma(dE/dx) = 11\%$ (truncated mean on tracks with more than 30 ionization measurements),
 $\Delta P_T/P_T \approx 0.02 P_T$ (for tracks with more than 35 drift measurements).

Mechanically, the chamber is executed as two semi-cylinders. This allows rapid extraction of the chamber from the magnet gap, without the need for breaking the ISR vacuum of 10^{-12} Torr. Each half chamber is mounted on a "transparent" support, which also carries 3444 twisted-pair cables from the chamber preamplifiers and which in turn is riding on one half of the "bottom" uranium calorimeter (see fig. 5). Drift chambers and calorimeters are supported by a chariot riding on precision rails, which ensures positioning of such an assembly with a reproducibility of $\approx 100 \mu\text{m}$.

* It conforms, however, to even earlier investigations as summarized by the 12th century scholar William of Occam: "It is in vain to do with more what can be done with less".

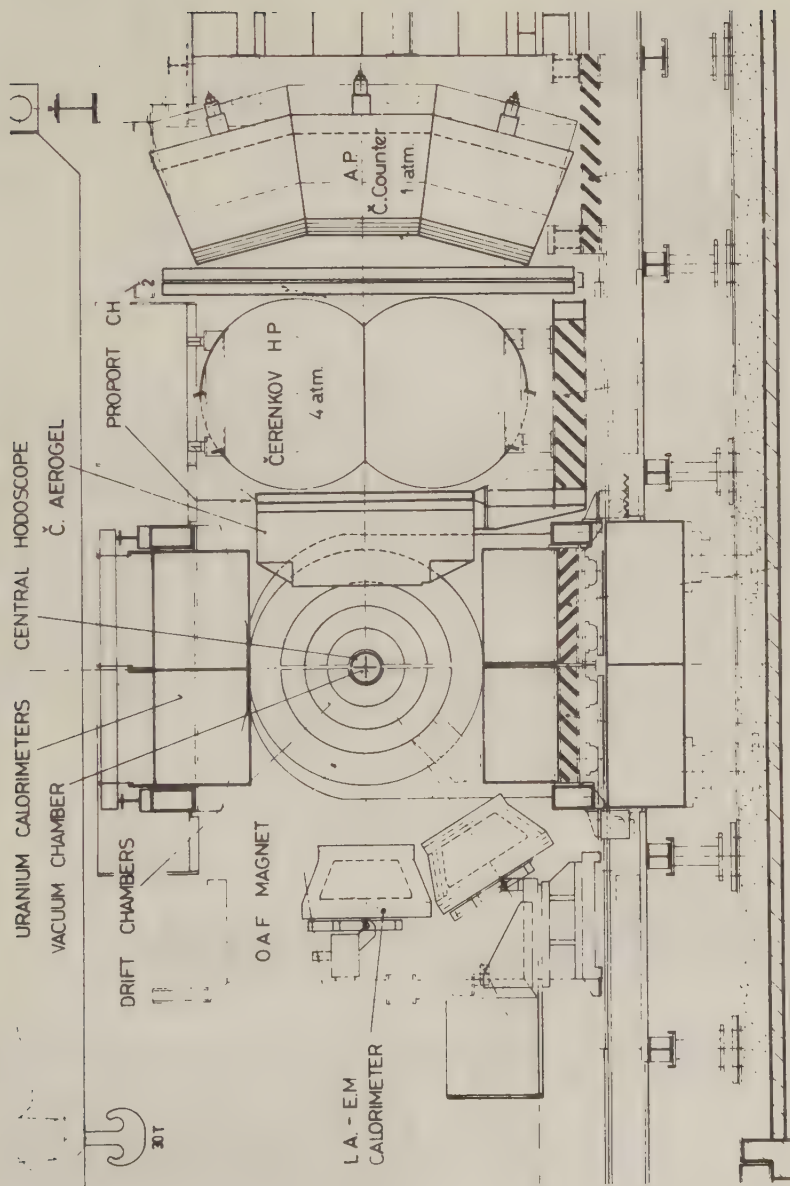


Fig. 1. Cross-section through the AFS (1981 configuration). The top and bottom U calorimeters (4 or total) are being installed during the first half of 1981.

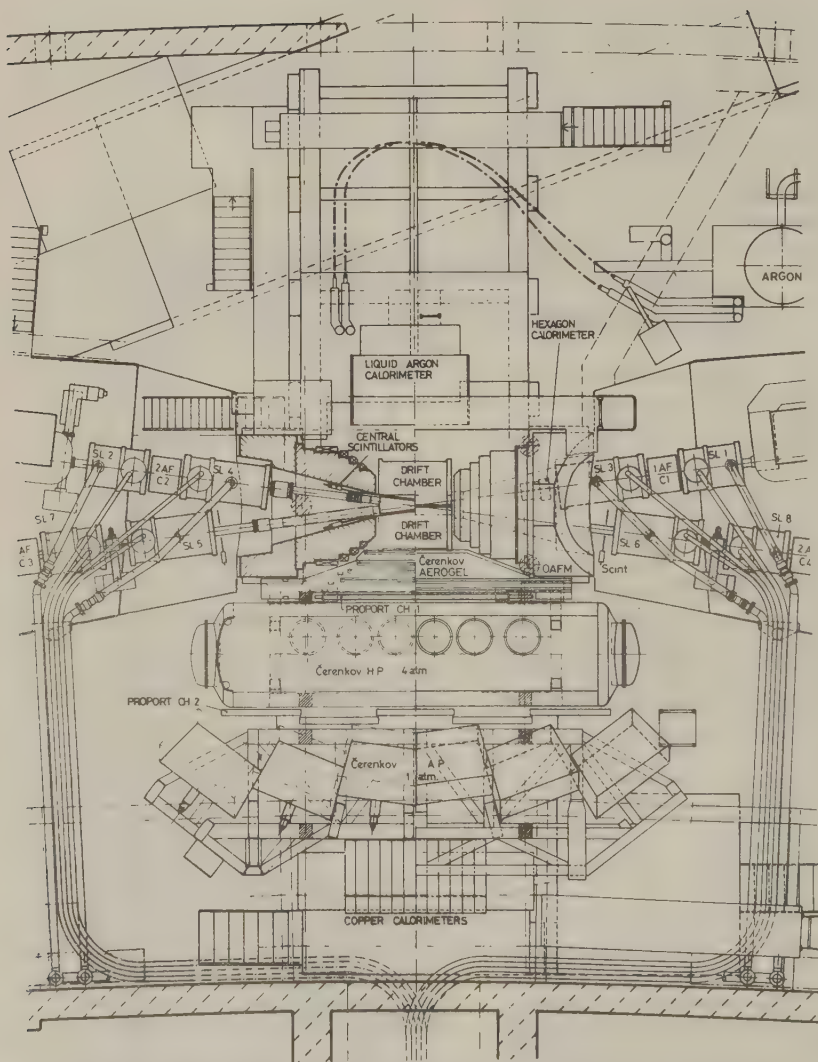


Fig. 2. Top view and horizontal section through the AFS (1981 configuration). It also shows the position of the eight superconducting quadrupoles (SL1 to SL8) of the newly operational low- β high-luminosity insertion.

2.3. Particle identification

Three threshold Cherenkov counters provide identification of relativistic particles over the solid angle of 1 sr (see figs. 1 and 2). The first counter contains a radiator

of silica aerogel [6] with a refractive index of $n = 1.05$; the second is a high pressure counter (HPC) filled with Freon-12 at 4 atm with a refractive index of $n = 1.004$; the third counter is operated, again with Freon-12, at atmospheric pressure ($n = 1.001$, APC). Multiwire pro-

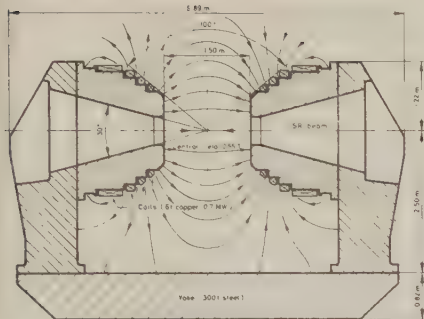


Fig. 3. Vertical cross-section through the open axial field magnet. The magnetic field lines show the direction and level of the field useful for momentum analysis and also the level of "stray field" in the external detectors.

portional chambers (MWPCs) with bidimensional read-out are mounted between the Cherenkov counters and used for triggering and tracking. The counters provide unambiguous identification from 2 to 12 GeV/c.

The relatively high multiplicity of high- P_T events determines the granularity of these counters. The aerogel Cherenkov is subdivided into 20 optical cells, four layers deep, the HPC into 12 and the APC into 18 cells.

Light from the aerogel blocks is projected onto thin wavelength shifters (WLSs); the shifted light is then guided through ~ 2 m long lucite light-guides to low stray field regions, where photomultiplier (PM) operation is relatively easy. Mirror systems are used for both gas Cherenkovs for light collection. Spherical mirrors (typically ~ 2 m² surface) focus the light onto flat mirrors, which are viewed by 5 in. PMs at the end of

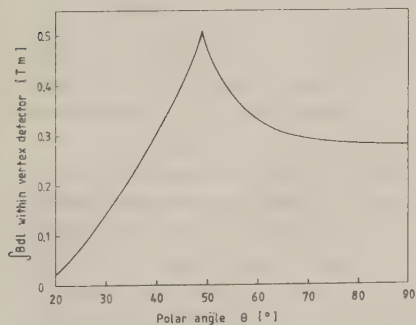


Fig. 4. The magnetic field component transverse to the trajectory of a particle from the vertex, integrated over the radial dimensions of the vertex detector (59 cm) as a function of polar angle (at a nominal power level of 700 kW).

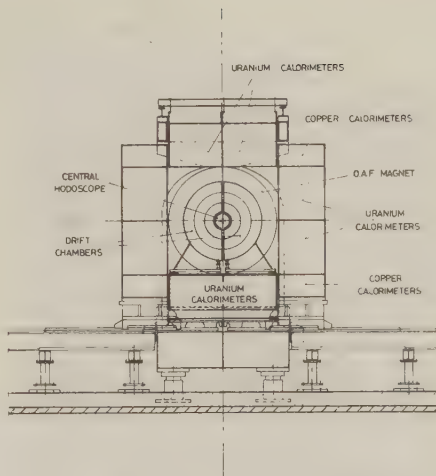


Fig. 5. Cross-section through the AFS showing the drift chamber surrounded by the 2π hadron calorimeter. This layout of the detector is planned for 1982.

Winston cones. Each cell of the HPC is viewed by two such Winston cone-PM combinations to achieve uniform efficiency for all particles originating from the ~ 60 cm long ISR interaction region. The design goals – uniform and good light collection inside a cell and relative to other cells – have been achieved as verified in extensive beam tests. For the HPC we measure, on an average, 25 photoelectrons for relativistic particles and 15 for the APC. An indication of the performance in the ISR is shown in fig. 6. A clear separation between pions and heavier hadrons is achieved, although no attempt has been made to remove background from δ electrons and γ conversions.

2.4. The hadron calorimeter

2.4.1. Principal considerations

While there are compelling physics reasons for using hadron calorimeters in colliding beam experiments, lack of adequate instrumental techniques has so far prevented their use. Only in recent years have calorimetry techniques been studied well enough [7], and suitable read-out techniques developed for sampling calorimeters [8]. Effective use of calorimeters at hadron colliders is particularly difficult for the following two reasons:

- 1) Invariant cross-sections fall steeply as a function of the transverse momentum, typically as P_T^{-9} ; measured spectra are smeared by the instrumental resolution and may therefore be grossly distorted (see fig. 7). Energy resolution is at a premium!

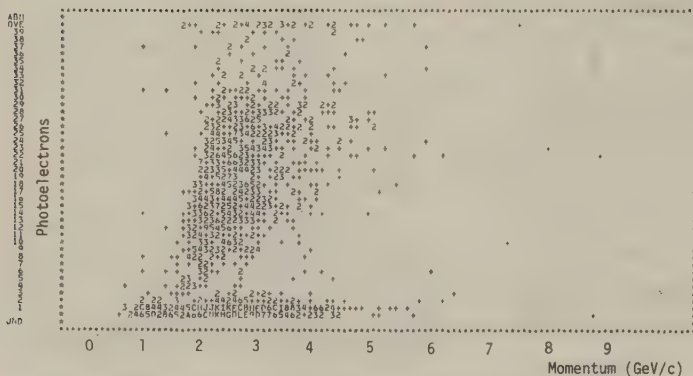


Fig. 6. The ISR performance of HPC, showing the number of photoelectrons as a function of particle momentum. The band of pions is clearly separated from the heavier hadrons.

2) At hadron colliders the calorimeters serve the additional, equally important role of very effective and highly selective trigger devices. Again, apart from the importance of energy resolution, the unbiased selection of final states is only possible if the calorimeters response is independent of the nature of the incident

particle: a truly democratic response is a necessity!

Both of the above requirements are elegantly optimized with the use of ^{238}U as the absorber plates [7] and we therefore adopted this material.

Another fundamental consideration is the "granularity" of such a detector, i.e. the solid angle covered by any read-out channel. The physics suggests a calorimeter granularity consistent with the measurement of individual particles even in highly collimated jets. This imposes a relation between the average absorption length (and hence the transverse dimensions of a hadron shower) and the average separation between the particles at the entrance face of the calorimeter. The high average density of our calorimeter ($\bar{\lambda}_{\text{absorpt}} = 22 \text{ cm}$) and the expected particle density in typical ISR jets of $P_T \approx 10 \text{ GeV/c}$ resulted in the present design: the entrance face of the calorimeter starts radially at a distance of 120 cm; the individual cell has an area of $20 \times 20 \text{ cm}^2$ and resolves $\geq 85\%$ of all particles in a jet.

2.4.2. Choice of read-out

Two techniques are available for the active read-out of calorimeters [9] which do not affect the intrinsic resolution for electromagnetic showers and which permit a very compact design. The liquid-argon technique, by now matured into a standard method, has proved its reliability and its excellent control of systematic effects at the 1% level. Although we considered it as our first choice, we shied away after initial indications that a surprisingly high premium would have to be paid for the small U plates required for the ion chamber electrodes. We settled for second best by adopting the WLS technique [10,11] for the scintillator read-out.

The method is sketched in fig. 8. As with all light-collection techniques, great care has to be given to:

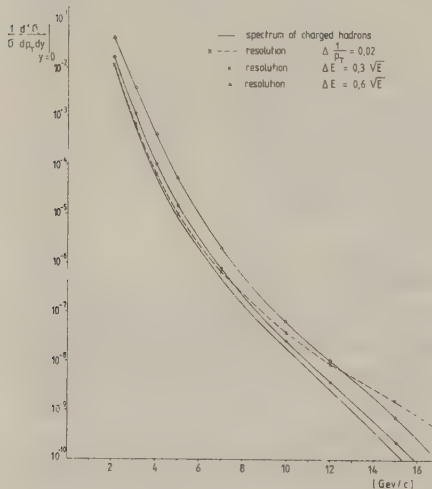


Fig. 7. Effect of detector resolution on a steeply falling particle spectrum, shown for three different resolution functions; $\delta(1/p) = 0.02$ represents the performance of our drift chamber; $\sigma(E)/E = 0.6/\sqrt{E}$ applies typically for a very good non-U hadron calorimeter, while $\sigma(E)/E = 0.3/\sqrt{E}$ is similar to the resolution of our U calorimeter.

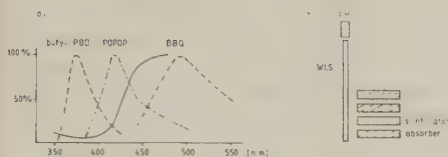


Fig. 8. Spectral response (a) and conceptual arrangement (b) of the scintillator-wavelength shifter system for sampling calorimeter. Light emitted from the scintillator (e.g. butyl PBD or POPOP) enters the wavelength shifter ("BBQ") across an air gap; it is subsequently absorbed and isotropically re-emitted at longer wavelengths.

- 1) minimize non-uniformities in the optical elements;
- 2) minimize dead-space introduced by the WLS bar; it must not have excess response (produced, for example, by Cherenkov light) to direct particle hits;
- 3) provide an adequate calibration for the complete read-out chain.

We arrived at the following optimization [12]. Plastic scintillator* based on PMMA (polymethyl methacrylate) was chosen for cost and mechanical reasons. It was doped with 1% butyl-PBD as the primary scintillating agent and 10% naphthalene was added to improve the light yield (measured to be about 70% of NE102A). No wavelength shifting material was used, as is commonly done ("POPOP"), resulting in a desired, strong absorption of the emission spectrum; we measured for our scintillator an absorption length of $\lambda = 30$ cm, consistent with our cell size. The WLS was again based on PMMA, doped with BBQ. Sufficiently high absorption of the scintillator light, consistent with adequate uniformity ($\pm 5\%$) along the WLS and sufficiently low response to Cherenkov light, was achieved with a 2 mm thick shifter, made from ultraviolet absorbing plexiglas 201**, and doped with 80 mg/l BBQ. Calibration of the complete read-out chain is in general one of the most serious difficulties of this optical technique. We avoided complex auxiliary optical systems by exploiting the natural radioactivity of our plates as the calibration reference. We find that in our stacks the charge measured from one of the PMs of the hadronic part of the calorimeter, during a $10 \mu\text{s}$ ADC gate, corresponds to the signal obtained from a ~ 4 GeV pion. In practice, the U signal of each assembled stack is cross-calibrated with cosmic-ray muons which establish an absolute energy scale. From the modulus constructed to date, we infer that the U radio-activity provides an energy calibration at the 1% level.

* Manufactured by Altulor S.A., Paris, France.

** Manufactured by Rohm GmbH, Darmstadt, Fed. Rep. Germany.

2.4.3. Mechanical construction of the calorimeter

The solid angle of 8 sr is covered with 128 identical "stacks" (fig. 9), arranged in four "walls", as shown in fig. 5. The corners of the walls are plugged with smaller stacks made of copper plates to contain approximately 3% of the energy, which would otherwise escape.

Longitudinally the calorimeter is subdivided into two parts. A 5-radiation-length deep electromagnetic (e.m.) part is read out separately from the 3.6-absorption-length deep hadronic section. The final disposition of the plates in a stack reflects the compromise between the requirements for good energy resolution and the wish to minimise the total amount of uranium and the required machining effort. The final optimization resulted in the choice of ten U plates, 2 mm thick for the e.m. part; the hadronic section consists of 38 cells, each composed of two 3 mm U plates followed by one 5 mm Cu plate.

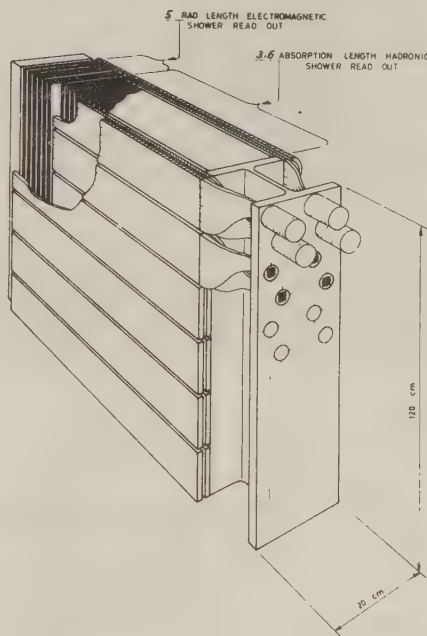


Fig. 9. Sketch of one of 128 calorimeter stacks. Each stack, mechanically homogeneous, is divided optically into 6 cells ($20 \times 20 \text{ cm}^2$), and each cell is read out on both sides and twice along the longitudinal direction. Note that the electromagnetic part uses ten 2 mm thick U plates, whereas the hadronic part is composed of seventy-six 3 mm thick U plates and thirty-eight 5 mm thick Cu plates. Scintillator of 2.5 mm thickness is used throughout. Each stack weighs about 2 t.

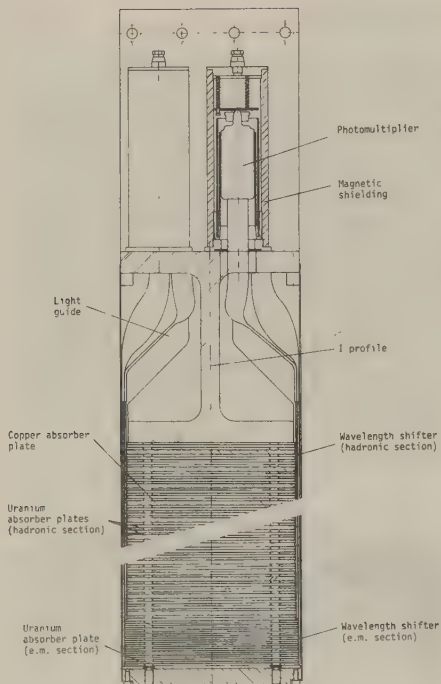


Fig. 10. Horizontal cross-section through a U stack.

In the mechanical construction we aimed – not forgetting ease and simplicity – to minimize dead areas due to structural elements inside the stack. The result is

shown in fig. 10. The plates are tied together with one 10 mm diameter rod; four 10 mm diameter spacers, located in corresponding holes in the corners of the scintillator, and one washer, around the central rod, space the U plate and prevent pressure contact with the scintillators. Constructed in this way, the stacks are self-supporting in four different positions (fig. 5).

Assembly time, including mounting of the WLSs and PMs, requires eight man-days per stack. So far, we have constructed one wall and completion of the calorimeter is scheduled for the summer of 1982.

2.4.4. Performance

Our choice for the light absorption length in the scintillator combined with the read-out arrangement provides excellent position resolution in both transverse directions of a stack. An example is shown in fig. 11, from which one may also judge the optical uniformity of our design. Typically we find for a few GeV/c electrons a spatial resolution of $\sigma_x \approx \sigma_y \approx 10$ mm.

The energy resolution for electrons and hadrons as a function of incident angle into the stack is given in fig. 12. The electron resolution is consistent with the value expected from sampling and photon statistics (300 photoelectrons per GeV). The hadronic resolution reflects the intrinsic resolution of an ideal U calorimeter of

$$\sigma_{\text{intrinsic}}^U/E = 0.2/\sqrt{E} \text{ (GeV)},$$

and the sampling fluctuations, estimated to be

$$\sigma_{\text{sampling}}^U/E = 0.1 \sqrt{\frac{\Delta E \text{ (MeV)} \text{ gap}}{E \text{ (GeV)}}} \approx 0.25/\sqrt{E},$$

where ΔE is the energy loss per U cell; $\Delta E \approx 6.5$ MeV. The twofold longitudinal read-out combined with good spacial resolution permits considerable electron/pion discrimination. We find a pion rejection of larger than

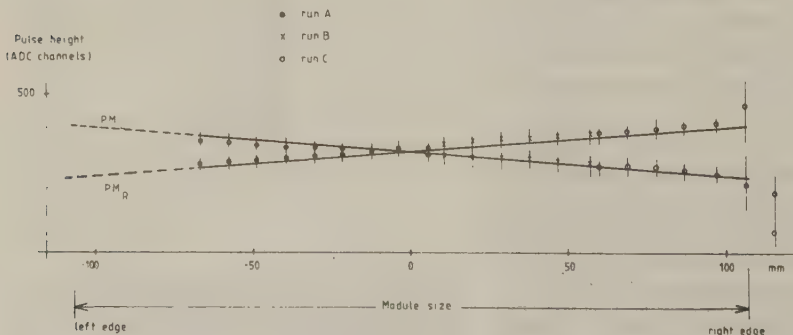


Fig. 11. Mean pulse height as a function of position for 5 GeV/c electrons. The error bars indicate the fwhm of the pulse-height distributions.

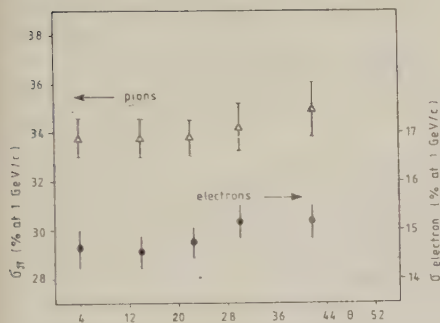


Fig. 12. The normalized energy resolution for electrons and hadrons as a function of incident angle. The angle θ is measured with respect to normal incidence.

50 with $\sim 80\%$ electron acceptance, if complete shower information is available.

3. The AFS trigger system and on-line processors

The AFS is mostly used to study interactions with cross-sections in the microbarn to nanobarn range, frequently in an environment of very high collision rates (without the low- β insertion a typical luminosity of $L = 2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ implies a particle flux of $> 10^7 \text{ s}^{-1}$ into a 4π detector). Central to efficient study of these relatively "rare" events are trigger and filter schemes, matched in processing power to the primary interaction rate and of sufficient discrimination to permit practical off-line analysis.

On-line processors were developed to evaluate the drift-time information from the central detector, hit patterns from the MWPCs of the Cherenkov arm, and the energy deposition in the calorimeter.

Selection of high- P_T charged particles proceeds through a sequence of increasingly more selective conditions [13]. A rejection of several hundred is obtained in a processing time of less than $1 \mu\text{s}$, by using position information on the drift and MWPC wires [14]. Ultimate rejection of up to about 5000 is based on the drift-time information for sagitta evaluation with a very fast parallel processor, ESOP [13]. Event purity (i.e. the fraction of tracks with P_T above threshold) is $\sim 10\%$; the trigger efficiency at threshold is $\sim 10\%$; and rises to a plateau at $\sim 50\%$. Inclusive spectra up to $P_T = 10 \text{ GeV}/c$ have been recorded in this way.

The trigger processor for the calorimeter is at present being brought into operation. For this purpose the dynode signals from the 3200 individual signal channels are summed over all cells of the same azimuth ("row")

for both the e.m. and hadronic segments. This results in 48 primary e.m. signals, and 48 U and 4 Cu-module hadronic signals. These 100 signals are transmitted via air core cable ($v = 0.95c$) to the counting room for further processing. As indicated in fig. 13, the hadronic sums of adjacent rows are combined, with an overlap of one row. Triggering on energy deposition in such a narrow slice will preferentially select configurations where most of the energy is carried by a single hadron. Similarly, six rows of cells ($\Delta\Omega \approx 1 \text{ sr}$) are combined into "jet sums" to achieve sensitivity for topologies expected to be characteristic of "jet" structure. Again, a geometrical overlap of 67% in the jet sums minimizes edge effects in the azimuthal efficiency of the trigger. The energy sums provide also a measure of the total deposited energy, E_{tot} , which is used as a pre-trigger and strobe for ADCs. A total of 123 fast, linear sums are generated in this way: 48 e.m. single particles (EM), 48 hadronic single particles (SP), 24 jet sums (JET), $E_{\text{tot}}(E)$, $E_{\text{tot}}(E_m)$, $P_{\text{tot}}(P_T)$. These sums are interrogated by multilevel discriminators (three levels for EM, five SP, four JET, six E , four E_m , three P_T), resulting in 493 signals. Subsequently, the definition of the e.m. single particle trigger is refined by requiring a spatial coincidence of an EM signal with a consistent value of an SP. All the information thus obtained is "multiplicity"-encoded, and transmitted in encoded form onto 33 signal lines. Other detectors (MWPCs and drift chambers), and in particular ESOP filtered tracks at different thresholds, may also be correlated with the calorimeter signals for which an additional 17 encoded lines are provided. Logic decisions on the information pattern present on these 50 signal lines are carried out by an array of high-speed logic units. Each distinct trigger pattern, represented by a unique signal pattern on the 50 lines, is stored in a 50-bit memory. This

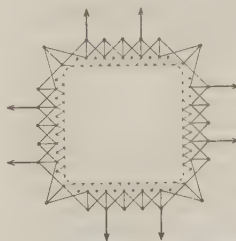


Fig. 13. Schematic diagram of the calorimeter trigger, which uses the information on energy distribution in the transverse plane. A small line segment in the inner square represents the summed up hadronic energy in a "row" of hadronic cells. The lines joining two rows give a "single particle sum", whereas the next level of summing over six rows represents the spatial extension of jets; further summing results in signals representing total energy deposition, E_{tot} .

Table 1
Selection criteria for some special final states ^{a)}.

Experiment	Trigger
1. Identified single-particle inclusive distributions and correlations	BB · ESOP(1) · 2 ⁻ⁿ ; E' · JET'(1) · ESOP(1); E' · SP'(1) · ESOP(1)
2. Identified pairs (pp, KK, ...)	BB · ESOP(2)
3. Jet studies and SP in calorimeter	BB · 2 ⁻ⁿ ; E' 2 ^{-m} ; E' · JET'(1) · 2 ^{-r} ; E' · JET'(2)
4. Flavour jets	E' · EM'(1) · ESOP(1); E' · EM'(2) · ESOP(2)
5. Multileptons (≥ 2)	E' · E' _{em} · EM'(2) · ESOP(2)
6. Inclusive electrons	E' · E' _{em} · EM'(1) · ESOP(1) · 2 ⁻ⁿ
7. Correlations	E' · SP'(2) · 2 ⁻ⁿ ; E' · JET'(2) · 2 ^{-m}

a) BB stands for "beam-beam" and represents an "unbiased" interaction trigger.

The superscripts *i, j, ...* indicate the minimum discriminator level and the subsequent higher ones.

Numbers in parentheses specify the multiplicity of a trigger condition.

2⁻ⁿ, 2^{-m}, ... give the down-scaling factors for abundant triggers.

arrangement allows parallel decision processing and down-scaling of abundant triggers. A partial list of various representative trigger combinations is provided in table 1.

Data from the drift chamber are recorded in 6888 ADC and 3444 drift-wire recorder channels. Pulse-height information from the full calorimeter will be contained in 3200 ADC channels. Data compaction is achieved on-line by a selective read-out of only those drift wires with a hit, and by using a fast processor to select the corresponding two ADC words; the same processor also groups data into a format, which is optimized for off-line analysis. A similar data compression is foreseen for the calorimeter information, using the ESOP processor. In this way the total number of data words is reduced to ~4000 for an average event, but still may be more than double for high-multiplicity events.

4. The AFS off-line software

For the present AFS experimental configuration the major part of the off-line data analysis consists of assigning drift-chamber digitizings to tracks, and then determining the momentum. (As calorimeter data become available, the analysis of this information will also constitute a significant part of the off-line programs.)

Sorting the digitizings into tracks is a classic problem of pattern recognition. In the transverse (*r, φ*) plane the track trajectory through the chamber is approximately a circle of radius *R*(cm) ≈ 700*p* (GeV/*c*). Hence for most momenta of interest (≥ 0.3 GeV/*c*) the radius is much larger than the arc length of the trajectory, which is

≥ 59 cm for a particle traversing the full chamber. Thus the trajectory can be approximated by:

$$\phi = \phi_0 + \alpha r,$$

i.e. a straight line in *r, φ* coordinates, with a slope related to the particle momentum.

The pattern recognition program proceeds by scanning the *r/φ* plane with a rotating "road", and counting the number of digitizing within the road. A genuine track or track segment will give a large digitizing count. The "left-right" ambiguity is then resolved by requiring that the digitizings be smoothly continuous rather than staggered by twice the sense wire staggering. Reasonable continuity in the *z* coordinate, derived from charge division, is also required at this stage. Finally track segments found within different roads are merged to form the full track. This pattern recognition program takes typically 2 s of IBM 168 time for an event of charged multiplicity 10.

The track digitizings are then passed to the momentum determination program. The procedure used is fairly standard. The time coordinate is eliminated from the equation of motion, resulting in expressions for $d^2(r\phi)/dr^2$ and d^2z/dr^2 . The trajectory is interpolated between the measurement points as a polynomial, so that the integration can be done exactly – the "spline" method. The program then determines the main vertex and secondary (decay) vertices from the fitted tracks. The pulse-height information at the ends of each sense wire, which provides the *z* coordinate, is also a measure of the energy loss, *dE/dx*. Given the number of *dE/dx* measurements, particle identification in the "1/β²" region is readily achieved.

It should be stressed that to obtain the best resolution from the chamber, careful studies must be made of topics like:

- 1) variation of the drift velocity over the drift region;
- 2) pulse-height dependent shifting of the measured time ("slewing");
- 3) cross-talk, etc.

The final program in the present chain studies the tracks going into the Cherenkov arm (see fig. 1). This involves extrapolating the tracks through the various Cherenkov counters and proportional chambers, and identifying the particle. The Cherenkov counters give $\pi/K/p$ separation over the 2–12 GeV/c range.

This large and complex off-line program chain is maintained on four different types of machine (IBM, NORD, UNIVAC, CDC) using the PATCHY system [15].

5. Status and prospects

During 1981 emphasis has been placed on the measurement of inclusive distributions of high- P_T hadrons. The year at the ISR was marked by the advent of proton-antiproton collisions, with exciting prospects for a number of very topical comparative studies. Physics with the calorimeter will finally begin this year, and subsequent years will see full exploitation of the unique experimental possibilities provided by the 2π calorimeter.

Is something missing from this splendid array of instruments? While clearly a substantial list of interesting detectors could be imagined, one notes in particular the lack of detection facilities for rapidities $|y| > 1.3$. It has been suggested [16] to equip the magnet poles with a fine array of proportional wires, thus extending the calorimeter coverage over two more units of rapidity. Preliminary engineering feasibility studies and test results [17] are encouraging. Recent physics results also remind us of the spatial coarseness of the e.m. part of the calorimeter: direct photons have been discovered at the ISR, and there is even an indication for direct γ pair production, yet we cannot detect such events with the Ucalorimeter: J/ψ 's and perhaps T 's are produced predominantly via the excited qq states and subsequent de-excitation via γ emission. Although 10^9 cc systems and perhaps 10^6 b $\bar{b}$ systems are being produced daily at the ISR, we are blind to such transitions. Soft and hard electrons of varied origins abound, but we have yet to paint a coherent picture and relate it to the underlying constituent dynamics. The list could be prolonged, but

all these phenomena could be studied if our present calorimeter were to receive a more fine-grained layer of e.m. shower detection. We are pursuing a variety of options to ensure the uniqueness of the instruments and hence its physics potential even beyond the time when we have stopped observing proton-proton collisions in the CERN ISR.

We are most grateful to the CERN management, who have supported the AFS project with foresight and conviction since its inception.

Our staff at the CERN EP, EE, DD, and ISR Divisions and at the collaborating institutions have worked with competence, dedication, and enthusiasm to provide us with a unique tool for studying high-energy collisions and we thank them for their contributions to the success of the apparatus.

References

- [1] T. Taylor, Contribution to the Workshop on Future ISR physics, CERN (1976), unpublished note.
- [2] L. Camilleri et al., Nucl. Instr. and Meth. 156 (1978) 275; A. Zichichi (Chairman), Results of the ISR working party on a new magnetic facility, CERN (1976) unpublished.
- [3] O. Botner et al., these Proceedings, p. 315.
- [4] The chosen geometry is similar to the "jet-chamber" of the JADE Collaboration, See, for example, J. Heintze, these Proceedings. We have benefited from discussions with Prof. J. Heintze and his group during the conceptual stages of this detector development.
- [5] J.C. Berset et al., Nucl. Instr. and Meth. 176 (1980) 251.
- [6] T. Akesson et al., Proc. Int. Conf. on Experimentation at LEP, Uppsala (1980).
- [7] C.W. Fabjan et al., Nucl. Instr. and Meth. 141 (1977) 61.
- [8] For an extensive review, see: S. Iwata, Nagoya Univ. Report DPNU-3-79 (1979).
- [9] For a comparison, see: C.W. Fabjan and H.G. Fischer, Rep. Prog. Phys. 43 (1980) 1003.
- [10] R.C. Garwin, Rev. Sci. Instr. 31 (1960) 1010.
- [11] First test results of this read-out technique were reported by A. Erwin et al., Proc. Calorimeter Workshop, FNAL (FNAL, Batavia, Ill., 1975).
- [12] O. Botner et al., Nucl. Instr. and Meth. 179 (1981) 45.
- [13] B. Heck et al., Proc. Europhysics Conf. on Computing in high energy and nuclear physics, Bologna, Italy (1980).
- [14] S. Jaroslawski, Nucl. Instr. and Meth. 176 (1980) 263.
- [15] H. Klein and J. Zoll, PATCHY Manual, CERN Program Library (January 1977).
- [16] I. Polk and W. Willis, ISABELLA Technical Note, unpublished.
- [17] T. Ludlam et al., BNL-28605, and Proc. IEEE Nuclear Science Symp., Orlando, Florida (1980).

An Aerogel Cerenkov Counter for the AFS Experiment

S. Henning, G. Jarlskog, U. Mjörnmark, A. Nilsson and L. Svensson

Physics Department, Lund University, S-223 62 Lund, Sweden

Received August 28, 1980; accepted September 9, 1980

Abstract

A large aerogel Cerenkov counter has been constructed for the open axial field magnets at the CERN ISR. Due to the detector position in a strong magnetic field, and limited space, an unconventional readout method has been employed using wave length shifter.

1. Introduction

The AFS detector shown in Fig. 1 is designed for detecting large $p\bar{p}$ events over most of the solid angle in proton–proton collisions at the CERN ISR. The central drift chamber of the detector has a nearly 4π coverage for measurements of charged particles. The longitudinal readout is accomplished by charge division, which at the same time provides the means of identifying low momentum particles from the ionization measurements. On one side of the drift chamber high momentum charged particles can be identified in a 1 steradian solid angle Cerenkov arm with three different threshold counters. The first counter contains a radiator of silica aerogel with the refractive index $n = 1.050$, the second is a high pressure (4.5 atm) freon counter with $n = 1.0045$, and the third is a freon counter (1 atm) with $n = 1.0010$. These counters will in combination provide the identification of charged particles (hadrons) over the range from 2 to 10 GeV/c, as illustrated in Fig. 2.

The aerogel used in this detector has been made by the Lund group. In an accompanying paper [1] the properties of the material and the procedure of production is described. The aerogel counter contains about 800 litres of gel.

The geometry at storage rings easily gives very large dimensions to Cerenkov counters unless they are placed close to the interaction region. In our case the positioning of the gas Cerenkov counters were partly constrained by the space available in the ISR tunnel, partly by the requirement of operating their 5" photomultipliers in the vicinity of the AFM. The aerogel counter had to be accommodated in the space between the drift chamber and the high pressure counter with a maximum depth of 76 cm and in the 3 to 4 kG fringe field of the AFM. These restrictions are quite severe and led us to design a rather unconventional modular counter.

2. Design considerations

Given the detector configuration of Fig. 1, and considering the magnetic field around the AFM, it is clear that it is difficult to find a convenient place for the photomultipliers. The most favourable position is in the 40 cm gap at the side of the magnet return yoke, next to the high pressure counter, where the fringe field of about 1 kG can be controlled without disturbing the field map in the centre.

The relatively high multiplicity in events characterized by large transverse energy flow, and the jet-like topology of such

events, makes it necessary to use a limited cell size to decrease the probability of double hits. Our requirement was that the cell size should not exceed 50 mstr, i.e., a granularity of about 20 for the 1 str coverage. The high pressure counter contains 24 cells and the atmospheric counter 18 cells from the same coverage.

Calculations demonstrated [2] that the restrictions on the geometry exclude an efficient solution using a conventional optical readout system with mirrors or diffuse reflectors and 5" photomultipliers. A larger detector depth would have been required to accommodate the reflectors and the phototubes. Preliminary tests using wave length shifter indicated that this might be an adequate solution for the readout problem in our geometry, allowing for a small cell size and for the light to be guided out. In order to get enough Cerenkov light a sampling method had to be used, where signals are added from several cells in consecutive layers. This method has the drawback of the introduction of long light guides susceptible to give a background of Cerenkov light from being hit by random particles, and of having to apply cuts around the wave length shifters.

3. The aerogel detector

The modular structure chosen for our aerogel detector is shown in Figs. 3(a) and 3(b). The cells are arranged in four layers in depth. Each cell is 20 cm high and covers 22.5° in polar angle. The vertical cut shown in Fig. 3(a) is the layout in the angular range 67.5°–90° to the intersecting beams. In the range 45°–67.5° there is one more cell in each layer. The radiator thickness in the cells is normally 8 cm, but restrictions in space due to the cabling of the central drift chamber limits the thickness of the first layer to 5 cm for most cells.

The aerogel is followed by a semicylindrical mirror of aluminized mylar, backed up by black cardboard, with a 4 mm thick and 10 cm wide sheet of wave length shifter placed as a radius in the cylinder along the full length of the cell. In order to minimize the probability of traversals for high momentum particles, the sheet is rotated so that it defines a plane including the intersection point of the beams.

The active agent in the wave length shifter is BBQ, in the concentration of 90 mg per litre of plexiglas 218. The geometry for the light collection is such that any photons leaving the back surface of the aerogel radiator will intersect the wave length shifter after only one reflection on the mylar mirror. However as seen in Fig. 4, only a part of the spectral range is absorbed by the BBQ, and only a fraction of the absorbed light is re-emitted in a direction suitable for being trapped by internal reflection in the light guide.

The photomultipliers have a common magnetic shield of 5 cm soft iron, which reduces the magnetic field from about 1 kG to about 200 G or less, adequate for the standard photomultiplier housing. The shapes of the light guides are fairly

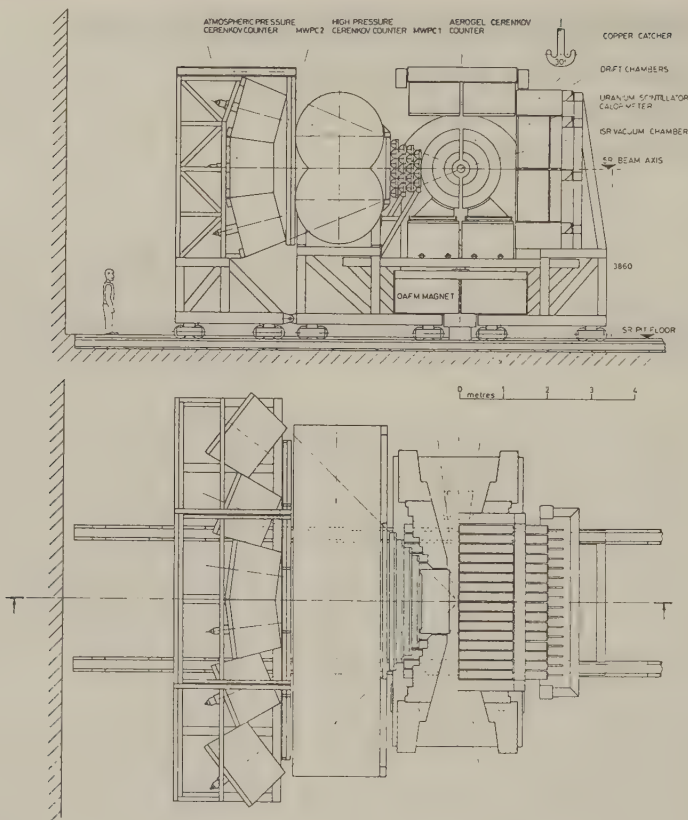


Fig. 1. Layout of R807.

complicated, and due to somewhat primitive facilities at Lund the light guides are not quite optimal in performance. The photomultipliers are standard 2" tubes (not selected). They are run at a fairly high voltage in order to record the signals from a single photoelectron.

Each cell is calibrated using a light diode, set to give a yield of about 5 photoelectrons. The position and width of the peak serves to calibrate the ADC (once the pedestal value is known). A 90 ns gating signal is derived from a scintillator barrel hodoscope surrounding the intersection region.

4. Expected performance

The number of photons emitted in the Cerenkov process is, given by

$$N(\lambda_1, \lambda_2) = 2\pi\alpha L \int_{\lambda_1}^{\lambda_2} \frac{\sin^2 \theta}{\lambda^2} d\lambda,$$

where α is the fine structure constant and L is the particle path in the radiator. Considering the absorption spectrum of BBQ (Fig. 4) and the self-absorption in the aerogel, it is clear that it is mainly the Cerenkov light emitted within the range 350

to 450 nm that gives the signal. Figure 5 shows the number of produced photons in a 10 cm long radiator with $n = 1.05$ within this interval as a function of particle momenta (neglecting the absorption in the gel). Figure 6 shows the results of a transmission measurement through 10 cm of gel. The fraction of unscattered light is at most 0.1 in the wave length interval considered. A rough estimate of the number of detected photoelectrons can be made. Several reduction factors apply:

- (i) 0.5 for the absorption or large angle scattering (more than 90°) in the aerogel.
- (ii) 0.9 for the reflectivity of the mirror.
- (iii) 0.2 for the trapped portion of the isotropically emitted light by the BBQ.
- (iv) 0.5 for the losses in the light guide.
- (v) 0.2 for the average photocathode efficiency over the BBQ emission spectrum.

Assuming that 120 primary photons are produced in 8 cm gel for $\beta = 1$ particles we would expect to detect about 1 photoelectron, corresponding to a detection efficiency of 63%. The addition of signals from three cells would give 96% detection efficiency which was considered worth while. Early tests with

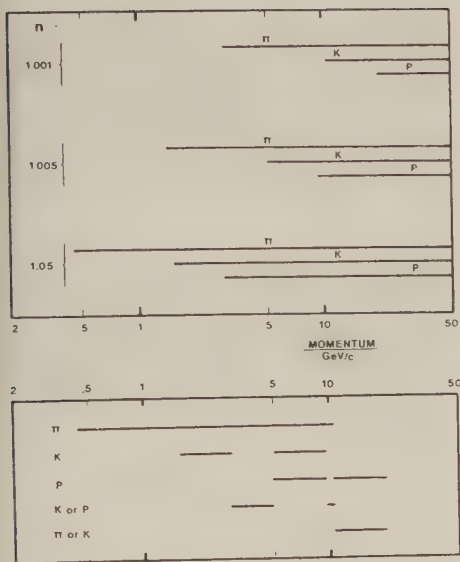


Fig. 2. The intervals where a set of three Cerenkov counters give signals are shown. The combination of the signals allow particle separation within the limits indicated in the lower graph assuming full efficiency from the threshold.

varying thickness of aerogel (and a rather short light guide) agree with this calculation (Fig. 7). From the saturation in the number of photoelectrons with thickness the conclusion was drawn that it is more useful to increase the number of samples rather than increasing the thickness of gel in fewer samples.

5. Actual performance

Eight of the final cells and light guides were tested in a negative pion beam at the CERN PS. The layout was identical to Fig. 3(b), so that all types of cells could be tested. The box containing the test modules could be rotated around the beam to simulate the intersection point at the ISR. Scintillation counters defined a beam of particles 9 mm high and 50 mm wide.

Figure 8 shows the results of a momentum scan through the four outer modules at the polar angle of 60° . The first layer contains in this case 5 cm of gel and the other three layers 8 cm of gel. The sum of the four signals gave for $\beta = 1$ particles an average of 3.0 photoelectrons in rather good agreement with the rough estimate of 4 (see above). The four inner modules with the longer light guides gave only 2.0 photoelectrons, indicating a larger loss of light in the light guides by 30–40%.

The uniformity of light collection within a cell was investigated by horizontal and vertical scans. Figure 9 shows a scan along a cell at 5 cm from the edge. The detection efficiency is nearly uniform as could be expected when most of the light is scattered through large angles. Small modulations may be seen at the boundaries of the aerogel blocks at 19 and 38 cm. The vertical scan shows a linear decrease in detection efficiency towards the edges corresponding to a change of 10% in the number of photoelectrons with respect to the centre. Particles

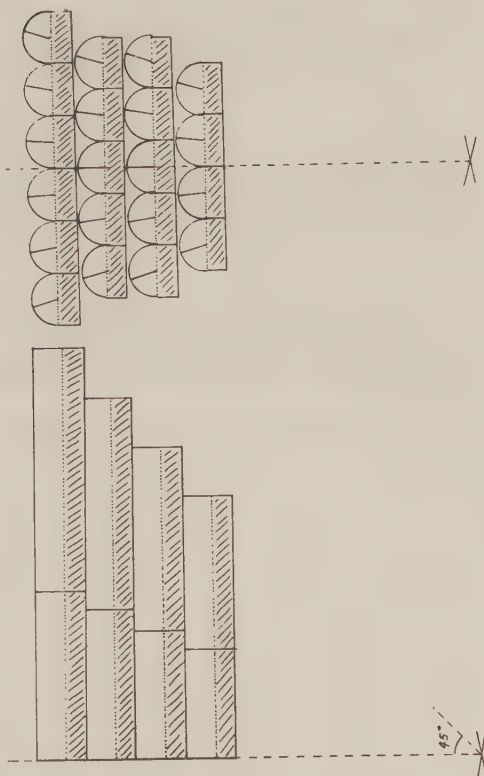


Fig. 3. (a) Vertical cut through the aerogel detector at the polar angle 90° . The height of each cell is 20 cm. (b) Horizontal cut showing one half on the aerogel detector (compare with Fig. 1).

hitting the wave length shifter produces pulses 5–10 times larger than the normal.

The detector was installed and set up at the ISR during the spring of 1980. Preliminary checks of the detector performance has been made during a week of running and a few tapes were written for off-line evaluation. During these tests layer 1 was not yet complete.

As seen in Fig. 1 there is a large multiwire proportional chamber, PC1, immediately behind the aerogel detector, so that tracks found in the central drift chamber can be extrapolated and checked in PC1. At the moment our software does not include the space point in PC1 in the fit of the trajectory. This creates a certain problem especially for the z-coordinate along the beams, where the charge division of the drift chamber only gives an extrapolation accuracy at the time of about 10 cm in PC1 making it difficult to define the cell boundaries. This is now being improved.

In order to determine the efficiency, groups of four consecutive cells were investigated. In the track extrapolation, from the drift chamber, the regions around the light guides were excluded. Later a discrimination against large signals (more than 4 photoelectrons) will be made. Two of the four cells were required to give a signal and the efficiency of the other two were

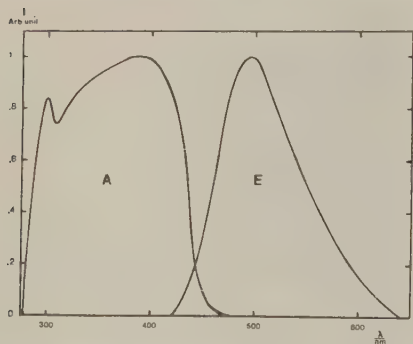


Fig. 4. Absorption (A) and emission (E) spectra for BBQ wavelength shifter.

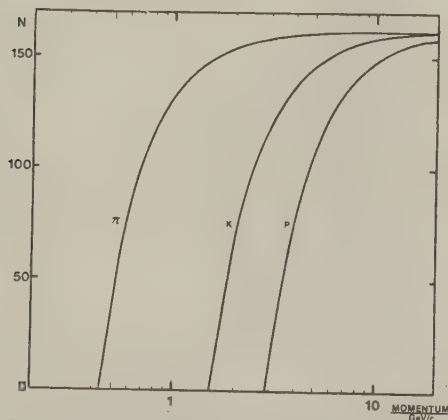


Fig. 6. Transmitted unscattered light, I , as function of wavelength, λ , for 10 cm aerogel of refractive index 1.05.

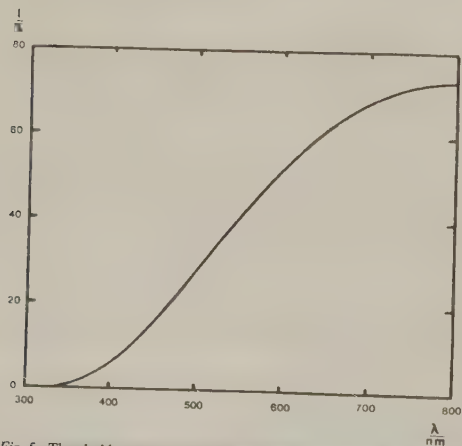


Fig. 5. Threshold curves for pions, kaons and protons for 10 cm aerogel of refractive index 1.05. N is the number of photons emitted in $350 < \lambda < 450$ nm.

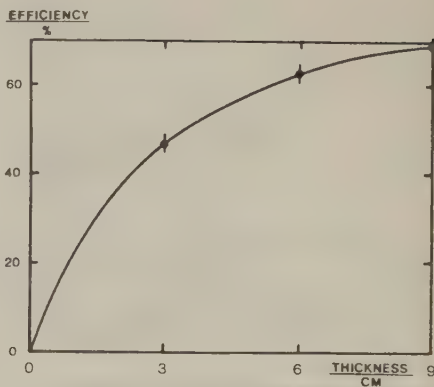


Fig. 7. The efficiency as function of aerogel thickness, giving an absorption length of 6 cm.

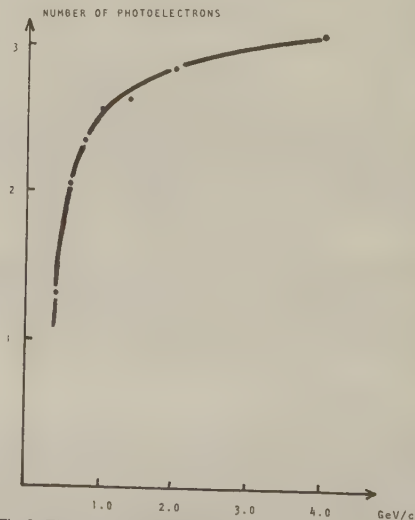


Fig. 8. The average number of photoelectrons from the added signals of four consecutive cells.

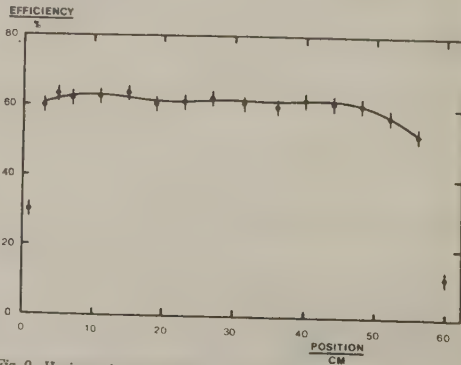


Fig. 9. Horizontal scan. The PM-tube is placed to the left.

investigated. Our first results are based on an event sample of 800 high momentum particles with the average momentum 3 GeV/c, identified as pions by the high pressure Cerenkov counter. Within the limited statistics the results indicate the following: the outer cells give an overall average of 0.55 photoelectrons per cell, while the inner cells give 0.36. The best cells are, as expected, the ones with the shortest light guides, i.e., layer 4 with 0.68 and 0.46 photoelectrons for the outer and inner cells respectively.

6. Conclusions

The results from the ISR must be considered as lower limits for the efficiency awaiting the full reconstruction program with PC1 and additional tuning of the photomultipliers. The lower limits for $\beta = 1$ particles are 2.4 photoelectrons for the outer cells and 1.6 photoelectrons for the inner cells. Although this number may seem marginal, it nevertheless implies that

about 70% of the charged kaons in the momentum interval of 2–3 GeV/c can be identified in conjunction with pion rejection in the high pressure Cerenkov counter.

Acknowledgements

We acknowledge the valuable help of Dr L. Jönsson for doing early calculations on the light yield and for the manufacture of the finger light guides, Prof. G. von Dardel for preparing the light guides at Lund, and Mr B. Goret and his collaborators in the CERN EF Division for making the support structure and the shielding for the photomultipliers.

References

1. Henning, S. and Svensson, L., *Physica Scripta* **23**, 697 (1981).
2. Henning, S., Jarlskog, G., Jönsson, L. and Svensson, L., Study of an aerogel Cerenkov counter for experiment R807 at the CERN ISR, LUNFD6/(NFL-7002).

Performance of an Aerogel Cerenkov
Counter using wavelengthshifter readout

A. Nilsson

Dept. of Physics, University of Lund

Abstract

A silica aerogel Cerenkov Counter has been built for the AFS experiment at ISR (R807). The aerogel has been produced and the counter assembled by the Lund group. Results from ISR are presented. The efficiency for high momentum π is 0.92 ± 0.02 in the most favourable part and 0.79 ± 0.01 in the least favourable. The efficiency is rather constant across the individual cells.

Performance of an Aerogel Cerenkov Counter using wavelength shifter readout

Introduction

A Silica Aerogel Cerenkov Counter has been built for the Axial Field Spectrometer (AFS) experiment^{*} at the ISR, CERN. The aerogel has been produced and the counter assembled by the Lund group. The counter was first installed in the ISR early 1980. The data used in these studies, around 20 000 tracks from α - α collisions, were taken during July 1980.

About the AFS experiment

The AFS (see fig. 1) consists of an (Open) Axial Field Magnet (OAFM) and a cylindrical drift chamber (ref. 7) surrounding the intersection region. On one side a Cerenkov arm and on the other sides the OAFM will be surrounded by uranium calorimeter stacks.

The Cerenkov arm consists of three different threshold counters containing: Aerogel-(AGC), High Pressure-(HPC) and Atmospheric pressure-(ATC) Cerenkovs. Between the AGC and the HPC and between HPC and ATC are placed two MWPC:s (Multi Wire Proportional Chambers) called PC1 and PC2 respectively. The Cerenkov arm covers about 1 sr ($\approx \pm 45^\circ$ in θ and $\approx \pm 30^\circ$ in φ). See further in refs. 1 and 2.

About the Silica Aerogel

Silica Aerogel (refs. 3 and 4) was developed as Cerenkov radiator to fill the region of refractive index n around $n=1.03$. Only gases under very high pressures (≈ 25 bar) were available for this region earlier, and some liquides eg. He. To keep a gas under such high pressures needs thick containers that absorb, scatter and create particles and also have restricted shape.

* The R807 collaboration with groups from Brookhaven, Copenhagen, CERN, Lund, Rutherford and Tel-Aviv.

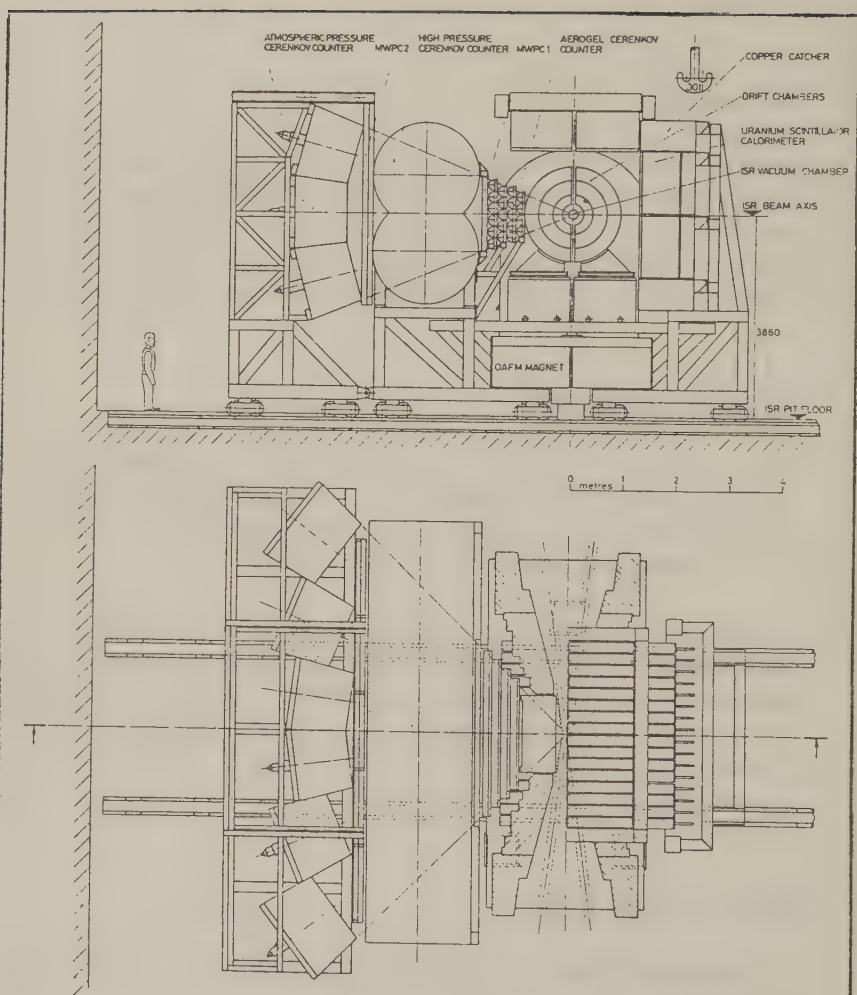


Fig.1. Layout of R807

The aerogel is a diffuse structure of SiO_2 which is solid but fragile. The density is $\rho \approx 0.25 \text{ g/cm}^3$. One radiation length of SiO_2 is $X_0 = 17 \text{ g/cm}^2$, i.e. $X_0/\rho \approx 68 \text{ cm}$. Aerogel can be produced with refractive indices in the region $1.01 \leq n \leq 1.06$. We have used $n=1.050$. This gives the following thresholds θ (= momentum for π , K, p at $\beta=1/n=0.954$. $\theta = m\beta = m_0\beta\gamma = m_0\beta(1-\beta^2)^{-1/2} = m_0(1-n^2)^{-1/2}$):

$$\theta_{\pi} = 0.44 \text{ GeV/c}$$

$$\theta_K = 1.54 \text{ GeV/c}$$

$$\theta_p = 2.93 \text{ GeV/c}$$

See further refs. 3 and 4.

About the Aerogel Cerenkov Counter

The counter (figs. 2a and 3) contains about 850 l of aerogel distributed in 88 cells with separate readout. The readout is done by the means of a WLS (Wave Length Shifter) bar (Plexiglas doped with 100 mg/l BBQ) coupled to a PM via a Plexiglas lightguide (see fig. 2b). The signals from the PM:s are recorded in charge sensitive ADC:s. The total physical size of the assembly is roughly 5 m long, 2 m high and 0.8 m deep.

An aerogel cell is 20 cm high, between 49 and 84 cm long and about 20 cm deep. The aerogel thickness is 8 cm for most cells.* The light collecting system behind the aerogel contains a WLS which is tilted so as to minimize the cross section seen by a straight line from the vertex or intersection region (see fig. 3). The semicircular wall of the cell is covered with highly reflective aluminized mylar. (See figs. 2a and 3 and ref. 2). The 88 cells are grouped in four layers and four columns as shown in fig. 2a. The total aerogel thickness is roughly between 27 and 32 cm. 32 cm corresponds to $32/68 = 0.47$ radiation lengths.

* The cells in layer one has 5 cm aerogel in the outer columns and 7 cm in the inner columns. The cells in layer three has 8 cm aerogel in column 2 and the other columns have at the moment only 6 cm. All other cells have 8 cm aerogel.

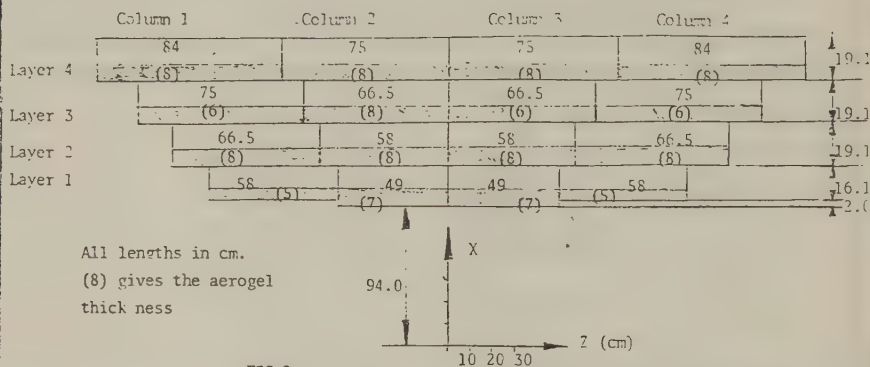


FIG 2a

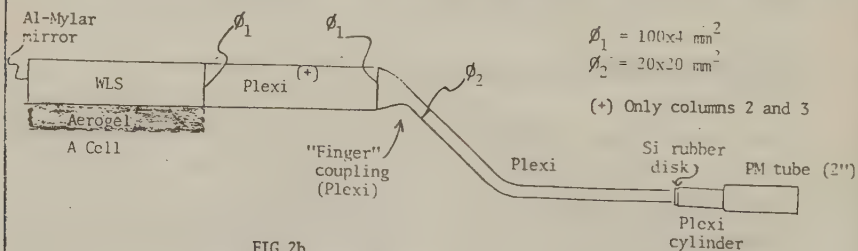


FIG 2b

Light collecting system.

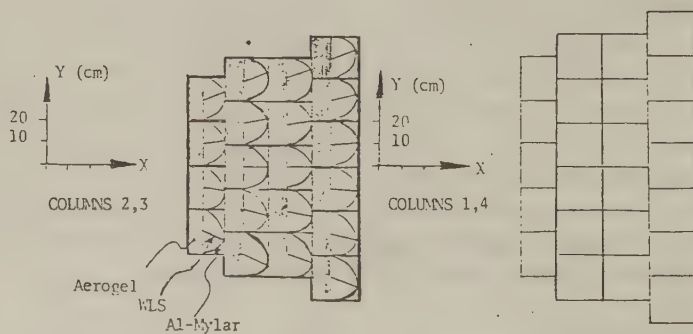


FIG 3

Backgrounds

The probability that a high momentum particle will knock out an electron (δ -ray) that will be energetic enough to produce Cerenkov light in the aerogel is less than 10% per cell. The number of δ -rays per track $N_\delta = \int_{E_{\min}}^{E_{\max}} W/E^2 dE$ where $W = 0.15 \text{ MeV}/\beta^2$ and E is the kinetic energy of the electron. $E_{\min} = 1.2 \text{ MeV}$, $E_{\max}$ is dE in dE/dx , $dx = 8 \text{ cm} \cdot 0.25 \text{ g/cm}^2 = 2 \text{ g/cm}^2$. dE/dx is $\approx 2 \text{ MeV/g/cm}^2$ so we get $E_{\max} \approx 4 \text{ MeV}$. (See ref. 5). A second background is caused by hits in the WLS and lightguides. The Cerenkov light produced in these is around 18 times as intensive as the Cerenkov light produced in the aerogel per unit length, L , for $\beta = 1$ particles. The number of photo electrons produced are $N(\lambda_1, \lambda_2) = 2 \pi \alpha \cdot L \cdot (1 - 1/n^2)(1/\lambda_1 - 1/\lambda_2)$ for $\beta = 1$, with $n = 1.05$ and 1.50 for aerogel and plexi respectively. $\lambda_1 = 350 \text{ nm}$ for aerogel and $\lambda_1 = 300 \text{ nm}$ for WLS and $\lambda_2 = 450 \text{ nm}$ where the limits are set by scattering and absorption of short wavelengths in the aerogel and by WLS absorption range (see ref. 3 and 6). The WLS is 4 mm thick, 10 cm deep and as long as the cell itself. For high momentum particles (straight lines) we thus expect the number of WLS hits to be $4 \text{ mm}/20 \text{ cm} = 2\%$ per cell.

Another background is caused by electrons from γ conversions (from $\pi^0 \rightarrow 2\gamma$). Finally the PM noise will contribute to the general noise.

Calibration Procedure

To be able to calibrate every cell in the counter we glued LED:s onto the WLS. In the calibration we set the LED drivers to produce between 5 and 10 photoelectrons. The probability distribution is Poisson-like. Measuring the peak position and FWHM gives a measure of the number of photoelectrons $\bar{k}$, $\bar{k} = (\text{peak}/\delta)^2 = (\text{peak} \cdot 2.3/\text{FWHM})^2$ as for a Poisson $\bar{k} = \text{peak} = \delta^2$. If $\bar{k}$ is big enough a Poisson can be approximated by a Gaussian for which $\delta = \text{FWHM}/2.3$.

The calibration was done to find out how many photoelectrons that corresponds to one ADC channel and also as a way of monitoring the status of the readout system. The whole procedure was done with the online mini-computer. For further details on calibration please see the appendix.

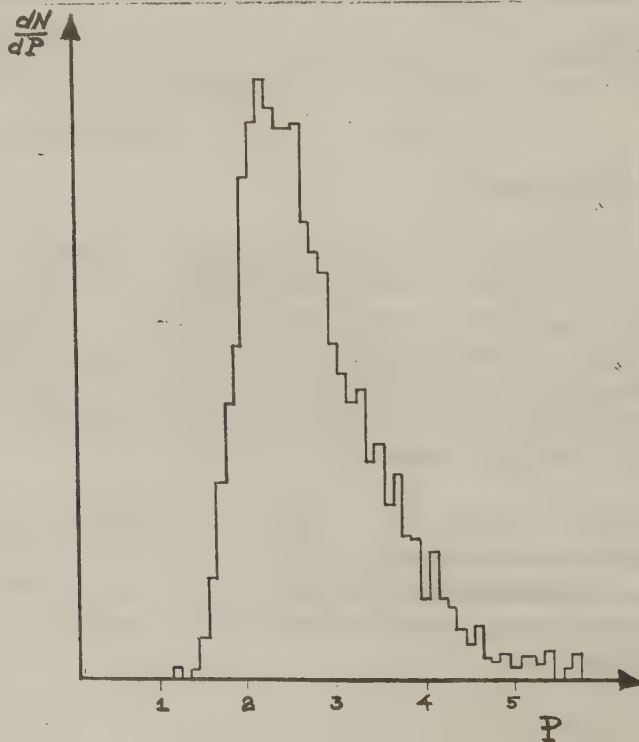
Data, data reduction and cuts on the data

To get a good sample of data some cuts have to be applied. The first are track quality cuts: the error in momentum measurement $dp/p < 0.20$ and the number of z digitizings in the drift chamber had to be > 20 , i.e. at least 20 out of 42 wires must have Z-information (along a wire, see coordinate system in fig. 2). Another cut is done in PC1. To follow a track through the aerogel a tracking or extrapolation from the drift chamber out through the Cerenkov arm taking the magnetic field into account is done. This tracking has to agree with measured points in PC1:

$$|y(\text{tracked}) - y(\text{measured})| < 1.5/p_T + 1.25 \text{ (cm)}$$

$$|z(\text{tracked}) - z(\text{measured})| < 10 \text{ (cm)}$$

About 50% of the 20 000 tracks survive these cuts i.e. around 10 000. Only around 15% of these pass through each of the outer columns 1 and 4. Further the trigger used in data taking had a momentum threshold set in such a way that only trigger tracks corresponding to particles with momentum $p \geq 1.4 \text{ GeV/c}$ were recorded. See momentum distribution in fig. 4.



During the tracking a test on WLS hits along the track is done as well as for other tracks hitting the WLS or lightguide of a cell. If any such hits are found the signal of that cell is set to zero. Also if the signal is bigger than 4 photoelectrons the WLS is defined as hit and the signal is set to zero ^{*}.

The number of such cases is around 2% in the outer and 1.5% in the inner columns. The expected number of WLS hits is 2%, in close agreement with the found value.

Results

The following kinds of estimate have been done:

- 1 Efficiency for π around 3 GeV/c
- 2 " " K " 2.2 GeV/c
- and " " K/p " 3.5 GeV/c
- 3 " -scan across a cell.

1 Efficiency for π around 3 GeV/c

Two kinds of trigger were used, HPC trigger and two cell trigger.

HPC-trigger. The momentum range $1.4 < p < 4.9$ (GeV/c) is the π window for HPC. The mean momentum for the sample is between 2.7 and 3.2 (GeV/c).

* From tests done in the PM test beam at CERN, the mean number of photoelectrons per cell was found to be $\bar{k} \approx 0.5$. Assuming a Poisson probability distribution P in k we get

$$P(k > 4) = 1 - \sum_{i=0}^3 \frac{\bar{k}^i}{i!} e^{-\bar{k}} \approx 0.2\% \text{ for } \bar{k} = 0.5$$

This trigger is our cleanest way to select a π . In the two cell trigger a number of triggers can be K and p as well (see "Two cell trigger" below). The values for single cell efficiency ^{*}, defined as the number of signals seen divided by the number of tracks that passed through the cell is shown in table 1a together with statistical (standard) errors.

Column	1	2	3	4
Layer				
1	0.32±0.06	0.30±0.02	0.37±0.02	0.33±0.05
2	0.42±0.06	0.28±0.02	0.30±0.02	0.54±0.08
3	0.44±0.06	0.45±0.02	0.27±0.02	0.43±0.06
4	0.48±0.07	0.37±0.02	0.36±0.02	0.53±0.06

Table 1a

Single cell efficiencies from HPC trigger with statistical (standard) errors.

* We use the calibrated values (in terms of photoelectrons) only as a first estimate, i.e. to see if the signal >0.0 and in the case of WLS-hits to see if the signal >4.0.

Table 1b shows the total efficiencies for HPC triggers for columns 1-4. This is defined as

$$\bar{\epsilon} = 1 - \prod_{i=1}^4 (1 - \bar{\epsilon}_i)$$

where $\bar{\epsilon}_i$ is the mean single cell efficiency of layer i for a fix column. This $\bar{\epsilon}$ corresponds to the probability that at least 1 cell has a signal. Also shown in table 1b is the efficiency expressed in number of photo electrons $\bar{k}$ calculated as $(1 - \bar{\epsilon}) = e^{-\bar{k}}$ from a Poisson probability distribution where $P(k) = \bar{k}^k / k! * e^{-\bar{k}}$ and $1 - \bar{\epsilon} = P(k=0)$

Column	1	2	3	4
$\bar{\epsilon}$	0.89±0.02	0.83±0.01	0.79±0.01	0.92±0.02
$\bar{k}$ (range)	2.2(2.0-2.4)	1.8(1.7-1.8)	1.6(1.5-1.6)	2.5(2.3-2.8)

Table 1b

Total efficiencies ($\bar{\epsilon}$) from HPC trigger and corresponding number of photoelectrons ($\bar{k}$).

The probability to see a signal in 0, 1, 2, 3 and 4 cells per track using the HPC trigger results for single cell efficiencies in table 1a is shown in fig. 5. We have required that the "track" stays within one and the same column.

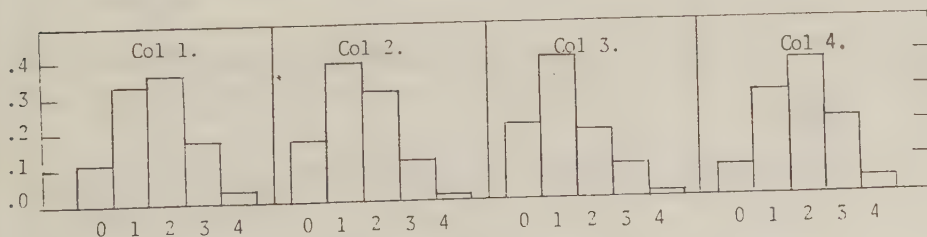


Fig. 5.

The probabilities ϵ_{234} to see signals in two or more cells per track is shown in table 1c (i.e. the sum of the last three bins in fig. 5 for each column).

Column	1	2	3	4
ϵ_{234}	56%	43%	39%	63%

Table 1c

The probability ϵ_{234} to see two or more cells with signal. (Calculated from HPC trigger).

Further, the same kinds of values as in fig. 5 and table 1c were found directly event per event counting when we actually saw 0, 1, 2, 3 and 4 cells per track. Table 1d shows ϵ_{234} , the probability to see at least 2 cells with signal per track, in mean for each column.

Column	1	2	3	4
ϵ_{234}	60%	43%	36%	54%

Table 1d

The probability ϵ_{234} to see two or more cells with signal. (HPC trigger, see text).

Thus the probability for a π around 3 GeV/c to be seen by at least two cells is about 60% in the outer and 40% in the inner columns.

Two cell trigger

For $p > 1.4$ GeV/c any two cells in the aerogel with signal > 0.0 , which the track has been extrapolated to pass through defines a two cell trigger for the other two cells. The number is not one but two to reduce accidental coincidences (background, noise). Three could also have been used but then the statistics is very low. The mean momentum for this sample is between 2.5 and 3 GeV/c. Here we can also trigger on K ($p > 1.5$ GeV/c) and p ($p > 3$ GeV/c) but we assumed all are π .

The single cell efficiencies are shown in table 1e and total efficiencies in table 1f (efficiencies defined as under "HPC trigger" above). One sees that these results are very similar to the HPC trigger results.

Column	1	2	3	4
Layer				
1	0.36 ± 0.07	0.29 ± 0.02	0.31 ± 0.03	0.38 ± 0.05
2	0.45 ± 0.06	0.29 ± 0.02	0.34 ± 0.03	0.50 ± 0.07
3	0.56 ± 0.10	0.45 ± 0.05	0.27 ± 0.03	0.37 ± 0.06
4	0.59 ± 0.11	0.36 ± 0.03	0.37 ± 0.03	0.46 ± 0.07

Table 1e

Single cell efficiencies from two cell trigger with statistical (standard) errors.

Column	1	2	3	4
$\bar{\epsilon}$	0.94 ± 0.02	0.82 ± 0.02	0.79 ± 0.02	0.89 ± 0.02
$\bar{k}(\text{range})$	2.8(2.5-3.2)	1.7(1.6-1.8)	1.6(1.5-1.6)	2.2(2.0-2.4)

Table 1f

Total efficiencies ($\bar{\epsilon}$) from two cell trigger with statistical (standard) errors and corresponding number of photoelectrons ($\bar{k}$).

We see that for both triggers the mean efficiencies per cell is around 45% in the outer and 35% in the inner columns, i.e. around 0.6 and 0.43 photoelectrons respectively. Cells in the inner columns are expected to be less efficient than in the outer for two reasons. Firstly they have longer lightguides. Secondly there is an angular effect, the cells are hit with an angle θ , which is bigger for the outer columns. The distance through the aerogel is then increased by a factor $1/\cos\theta$ and hence more Cerenkov light is produced.

2 Efficiency for K and K/p

To find other hadrons than π we antitrigger (veto) on the HPC in its π window ($1.5 < p < 4.9$ GeV/c) and at the same time we require two cells in the aerogel with signal, i.e. $\overline{\text{HPC}}^*(2 \text{ cells in AGC})$. The aerogel thresholds for K and p are $p=1.5$ and $p=2.9$ GeV/c respectively. Thus in this momentum range, $1.5 < p < 2.9$ GeV/c the above trigger should select K only and when $2.9 < p < 4.9$ GeV/s it should select K and p, not knowing which.

Only columns 2 and 3 had enough statistics for this kinds of estimates to be done so results are given for the inner columns only.

Kaon trigger, $1.5 < p < 2.9$ GeV/c

The mean single cell efficiencies are shown in table 2a for each layer. The mean is over columns 2 and 3.

Layer	1	2	3	4
$\bar{\epsilon}$	0.20 ± 0.10	0.26 ± 0.13	0.25 ± 0.13	0.27 ± 0.15

Table 2a

Single cell efficiency for K at $p=2.2$ GeV/c. Mean values for columns 2 and 3.

This gives a mean single cell efficiency for the whole counter of $\bar{\epsilon}=0.25\pm0.13$. The errors are (standard) statistical. The corresponding probabilities to see 0, 1, 2, 3 and 4 cells with signal as well as to see two or more, ϵ_{234} , are shown in table 2b. The values are calculated from the mean single cell efficiency $\bar{\epsilon}$ above.

N	0	1	2	3	4	ϵ_{234}
$\epsilon(N)$	0.32	0.42	0.21	0.05	0.004	0.26

Table 2b

The probabilities $\epsilon(N)$ that N cells have signal per track and to see two or more cells with signal (ϵ_{234}). Kaons.

The mean momentum for this sample was 2.2 GeV/c at which we expect the efficiency per cell to be $\epsilon=0.65*0.35=0.23$ (where 0.65 is the ratio between the number of photoelectrons for K at $p=2.2$ and $p=\infty$, see refs. 1 and 3. 0.35 is the single cell efficiency for π at $p=3$ GeV/c in the inner columns). This is close to the measured value $\bar{\epsilon}=0.25$ which give a total efficiency (i.e. to see at least one cell) of $\bar{\epsilon}_{\text{tot}}=1-(1-\bar{\epsilon})^4=1-(1-0.25)^4=0.68(\pm0.23)$, to be compared with the expected $\epsilon_{\text{tot}}=1-(1-0.23)^6=0.65$

p/K trigger. $2.9 < p < 4.9$ GeV/c

The values for single cell efficiency in this momentum interval is shown in table 2c.

Layer	1	2	3	4
$\bar{\epsilon}$	0.24 ± 0.15	0.36 ± 0.24	0.36 ± 0.24	0.25 ± 0.16

Table 2c

Single cell efficiencies $\bar{\epsilon}$ for K/p at momentum 3.5 GeV/c. Mean values from columns 2 and 3.

We get $\bar{\epsilon}=0.30\pm0.20$ as the mean in table 2c. Using this $\bar{\epsilon}$ we calculated the probabilities $\epsilon(N)$ shown in table 2d. The probabilities to see a signal in at least one cell (total efficiency $1-(1-\epsilon)^4$) is $\epsilon_{\text{tot}}=0.77\pm0.45$.

N	0	1	2	4	5	ϵ_{234}
$\epsilon(N)$	0.24	0.41	0.26	0.08	0.008	0.35

Table 2d

The probability $\epsilon(N)$ that N cells have signals per track and to see two or more cells with signal (ϵ_{234}), K/p.

The following conclusions can be drawn on K and K/p triggers. The probability to see a K in any out of four cells (in the inner columns) is ~ 68% for $p \sim 2.2$ GeV/c and to see a K in two or more cells of four is ~ 26%.

Because of low statistics no values for K efficiency was obtained for the outer columns. However in the measured π efficiencies we found the ϵ to be ~ a factor 1.13 and ϵ_{234} a factor 1.5 bigger in the outer than in the inner columns. Assuming this we get for the outer columns for K:

$$\epsilon'_{\text{tot}} = 1.13 * 0.68 = 0.77$$

$$\epsilon'_{234} = 1.5 * 0.26 = 0.39$$

For the K/p ambiguity interval we find in column 2 and 3 an ϵ_{tot} of 77% and a probability for at least two cells to register $\epsilon_{234} = 35\%$. Making again the assumptions used above we find for columns 1 and 4 the following efficiencies for K/p:

$$\epsilon'_{\text{tot}} = 1.13 * 0.77 = 0.87$$

$$\epsilon'_{234} = 1.5 * 0.35 = 0.53$$

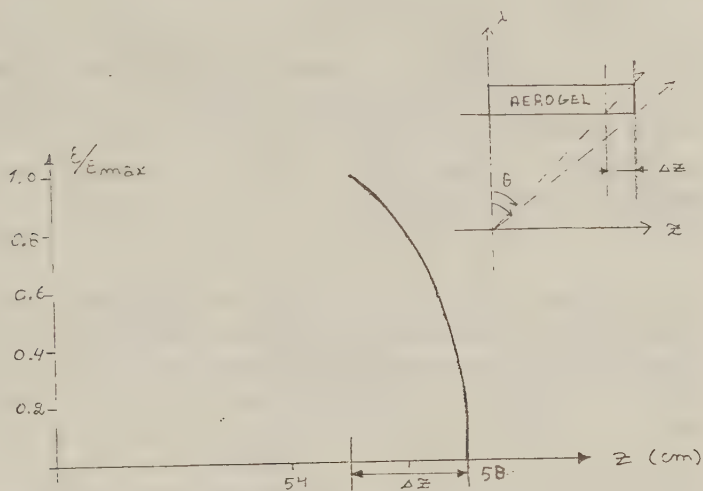


FIG. 6

Expected efficiency drop near the edge from the angle effect.

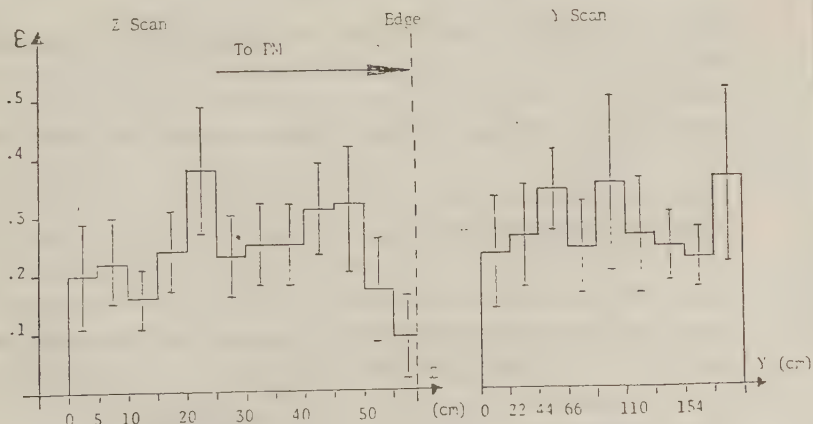


FIG. 7a

FIG. 7b

3 Efficiency scan across a cell

Two scans are presented, one horizontal (z scan) and one vertical (y-scan). A cell was defined as hit if a track was extrapolated to pass inside the boundaries of its front plane. This means that tracks passing close to the edge (under an angle θ) will eventually only partly pass through the aerogel. This effect is shown in fig. 6 for the z scan.

Because of low statistics results are presented for similar cells overlapped, using four cells in layer two from columns 2 and 3 (all 8 cm aerogel) which are placed symmetrically with respect to the xy and xz planes. This means that the four cells have their WLS:s tilted by the same angle φ and are also otherwise geometrically identical.

The results are shown in figures 7a and 7b for the z and y scans respectively. In fig. 7a can be seen an expected increase in efficiency towards the PM. It also exhibits the expected fall off from fig. 6. One expects this to occur within one bin in z but due to uncertainties in z from the extrapolation of the trajectory through Cerenkov arm ($\Delta z = 10$ cm in PC1) it will influence the two last bins, as is seen.

The y scan in fig. 7b shows an almost flat efficiency, although a small effect similar to the one in the z scan near the edge should be present in the last bin. The binning is also too wide for the WLS at y - 100 to be seen as its thickness is 4 mm and the binning 22 mm.

Appendix. Details of Calibration

In fig. 8 is shown the calibration setup. The online mini computer controls the test pulse generator which controls the timer. The timer has two outputs, one connected to the LED drivers and one to gate the ADC:s.

The calibration goes in two steps. First we make a "pedestal run" to find the channel in the ADC that corresponds to zero input. To do this we disconnect the LED-drivers from the timer at A and feed the system with typically 500 pulses. During the pedestal run the HT on PM:s was taken down.

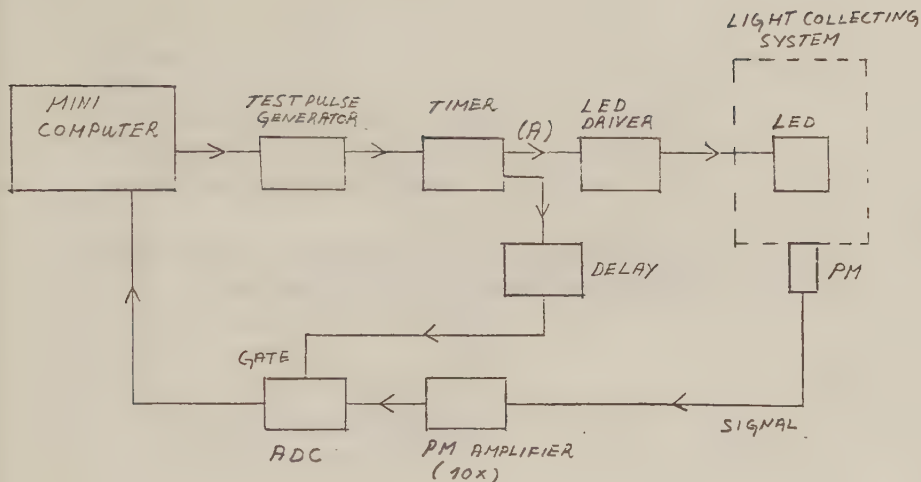


Fig. 8.

Secondly we feed the system with a larger (typically 10 000) number of pulses with A connected, to get the LED spectrum ("LED run"). From this LED spectrum the peak and FWHM are found and the peak is corrected for the pedestal and the number of photoelectrons $\bar{k}$ can be calculated as;

$$\bar{k} = \left(\frac{(\text{peak channel} - \text{pedestal channel}) * 2.3}{\text{FWHM}} \right)^2$$

and must fulfill $5 \leq \bar{k} \leq 10$

This range for $\bar{k}$ is chosen both to be big enough to let the Poisson distribution of the LED spectrum be approximated by a Gaussian distribution (so that $\sigma = \text{FWHM}/2.3$) and so that the range of the ADC (1024 channels) will cover all expected pulses from the counter (<4 photoelectrons). A typical spectra looks as in fig. 9b.

Then using this $\bar{k}$ a slope of the ADC can be defined as

$$\text{slope} = \frac{\bar{k}}{(\text{peak channel} - \text{pedestal channel})}$$

which tells the calibration value, i.e. how many photoelectrons one ADC channel corresponds to. This slope (one for each cell) is then used in

the analysis as

$$N(\text{cell}) = (\text{ADC channel} - \text{Pedestal channel}) * \text{slope}$$

where N is the number of photoelectrons and ADC channel the signal.

To be able to calculate $\bar{k}$ above, the FWHM must exist, i.e. a spectrum must have at least as many photoelectrons as in fig. 9a.

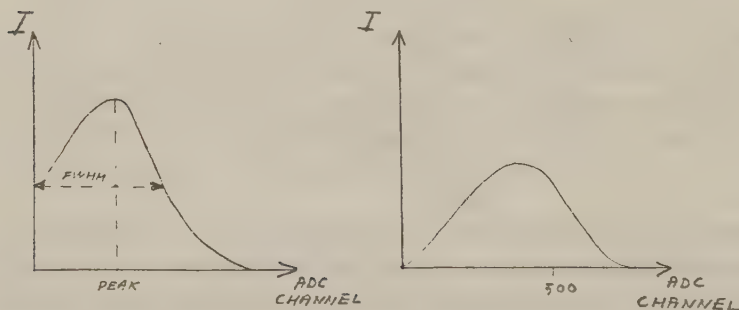


Fig. 9.

References

1. S. Henning, G. Jarlskog, L. Jönsson, L. Svensson.
"Study of an Aerogel Cerenkov Counter at CERN ISR".
LUNFD6/(NFFL-7002)/1-15/(1979).
2. S. Henning, G. Jarlskog, U. Mjörnmark, A. Nilsson.
"An Aerogel Cerenkov Counter for the AFS Experiment".
Physica Scripta vol. 23, p. 703.
3. S. Henning and L. Svensson.
"Production and development of Silica Aerogel".
LUNFD6/(NFFL-7001)/1-44/(1979).
4. S. Henning and L. Svensson.
"Production of Silica Aerogel".
Physica Scripta vol. 23, p. 607.
5. P. Rice-Evans.
"Spark Chambers, Proportional Chambers and Drift Chambers".
Ch. 1. (The Richelieu Press, London).
6. J. Litt and R. Meunier.
"Cerenkov Counter technique in High Energy Physics", Annual
Review of Nuclear Science, Vol 23, 1973.
7. T. Akesson et. al.
"Performance of the AFS vertex detector at the CERN ISR".
Physica Scripta vol. 23, p. 649.

Particle Physics Report

September 1983

LU-EP 83-05

LUNFD6/(NFFL-7018)/1-22(1983)

Ratios of inclusive particle production
at high transverse momentum
and
correlations between an identified charged particle at
high transverse momentum and identified associated charged
particles in pp collisions at c.m.s energy of 63 GeV.

The Åxial Field Spectrometer Collaboration

B. Lörstad and A. Nilsson

Departement of Elementary Particle Physics

University of Lund

Sölvegatan 14, S-22362 LUND

G. Damgaard

Niels Bohr Institute

Blegdamsvej 17, DK-2100 Copenhagen Ö

Abstract

Production of identified charged particles in pp collisions at c.m.s energy of 63 GeV with an identified high p_t trigger particle emitted in the central region is studied. The measurements were performed at the CERN ISR using the Axial Field Spectrometer.

Production ratios of identified charged particles to all charged particles are presented as a function of p_t in the range 5 GeV/c to 8 GeV/c. In addition the production ratio of charged pions to all charged particles is presented as a function of p_t in the range 2.5 GeV/c to 4.5 GeV/c.

The charge compensation in the hemisphere containing a high p_t trigger particle is shown to depend strongly on the identity of the trigger particle and on the identity of the associated particles.

The production rate of low momentum protons seems, however, not to depend on the trigger particle identity.

The away side charge structure is also studied. We find the positive to negative ratio of produced away side particles to depend on the trigger charge and to rise with p_t of the away side particles.

The data are compared with a simulation using the Lund model.

1. Introduction.

We report on measurements of identified charged particles produced in pp collisions at c.m.s energy of 63 GeV with an identified high p_t charged trigger particle emitted in the central region, with rapidity less than about 0.8.

It is well established that in general such collisions give rise to a 4-jet structure (refs. 1 and 2). In the hemisphere containing the high p_t trigger particle other particles of moderately high p_t are closely collimated around the trigger particle direction. In the opposite hemisphere (the away side) high p_t particles are well collimated in azimuth opposite to the trigger direction, but form, statistically, a broad enhancement in rapidity as the rapidity of the recoil jet varies from collision to collision.

First we present the ratios $(\pi^{+-})/(\text{all charged particles})$ in the p_t interval from 2.5 GeV/c to 4.5 GeV/c and the ratios $(\pi^{+-}), (K^{+-}), (p^{+-})/(\text{all charged particles})$ in the p_t region from 5 GeV/c to 8 GeV/c. Such ratios or cross sections have earlier been measured only at lower c.m.s energy or at lower p_t (ref. 3 and 4) apart from a measurement at 50° by the CDHW collaboration of the ratio of charged pions to all charged particles at the same c.m.s energy and approximately the same p_t range.

Next we will study charge correlations between an identified high p_t particle and associated identified charged particles. Similar measurements have been reported by the CDHW collaboration (ref. 1) and the BFS collaboration (ref. 2a). However, in most cases the associated particles were unidentified. Our results will be compared with a Monte Carlo model, the so called Lund model (ref. 6), where the parton-parton interactions are calculated in perturbative QCD to order α^2 taking care of color string configurations. These color strings fragment as observed in e^+e^- interactions.

As fragmentation is a soft process the primary quark is likely to be found in the high p_t trigger particle, giving rise to a particular correlation pattern: Fragmentation of a scattered parton have a charge compensating effect due to quark-antiquark pair creation. If, for instance, in a $\pi^+(ud)$ trigger the u is a scattered valence quark and the d quark comes from $d\bar{d}$ pair creation then the other member of the pair the $\bar{d}$ quark will form a $d\bar{q}$ meson which has zero or negative charge.

The compensation of charge is clearly seen experimentally between the fastest and the rest (see ref. 2a for the trigger side and ref.16 for the away side). Resonance production will influence the charge correlations but for certain combinations of identified particles effects due to quark fragmentation can be studied.

If the fragmentation of a parton is confined to one side only then the fragmentation giving rise to the trigger will not affect the away side. In the case of the Lund Model a string is stretched between the scattered partons which can lead to longer range correlations, however resonance decays will obscure these effects.

Further, as the proton contains two u and one d valence quarks, a scattered valence quark is more often a u quark leading more often to a positive than to a negative particle both on the trigger and on the away side, giving rise to a general charge pattern. In a naive parton picture no further correlation in charge or flavour is expected between two scattered partons as gluons are flavour and charge blind. Two gluon annihilation can give rise to a correlation in flavour and charge in the creation of a quark-antiquark pair, but QCD expects this process to be rare, in the the Lund Monte Carlo it contributes less than 1%.

This paper is organised as follows: Chapter 2 describes the apparatus and data analysis. In chapter 3 the inclusive particle production is studied with emphasis on ratios between different identities. Chapter 4 investigates the charge compensation versus rapidity calculated along the jet-axis given by the

trigger particle. Chapter 5 takes up production of low-momentum protons and antiprotons. Chapter 6 studies different aspects of away side correlations with the trigger particle. Conclusions end the paper.

2. Apparatus and data analysis

This experiment was performed at the CERN ISR using the Axial Field Spectrometer, shown in Fig. 1 in a view transverse to the colliding beams. The apparatus and its performance are described in detail elsewhere (ref. 7). Here we mention briefly only those components of the apparatus which were used in the present investigation.

The central cylindrical drift chamber is 1.4 m long and extends radially from 0.2 to 0.8 m. It is segmented azimuthally in 4° sectors each with 42 sense wires. In azimuth it provides a full 2π coverage except for two 16° wedges above and below the interaction region. It is situated in an axially symmetric magnetic field of 0.5 Tesla. Position coordinates in the plane transverse to the sense wires are determined by drift time and have a resolution of 230 μm . Along the wires, parallel to the beams, the position is measured by relative pulse height measurements at the two ends of the wires. The corresponding resolution is ~ 1.5 cm. The pulse height measurements also provide dE/dx information, used for particle identification. This gives π identification in the momentum range of 0.2 to 0.5 GeV/c, K identification in the momentum range 0.3 to 0.7 GeV/c and p identification in the momentum range 0.4 to 1.3 GeV/c.

Three sets of threshold Cerenkov counters subtend an azimuthal angle of 45° and $45^{\circ} < \theta < 135^{\circ}$ in polar angle. The Cerenkov counter closest to the drift chamber, the aerogel Cerenkov counter, consists of 88 cells arranged in 4 layers in depth. The cells are read out using wave length shifter technique. The average number of photoelectrons per cell produced by a $\beta \sim 1$ particle is only 0.3 as determined from data, resulting in an efficiency per track of around 80% for having at least 1 signal from the aerogel counter. On the other hand 20% of the tracks

with momentum below π threshold (0.5 GeV/c) have associated noise in the counter. In this study the aerogel counter makes it possible to identify π mesons in the momentum range of .5 to 1.5 GeV/c and to identify K mesons in the momentum range from 2 to 3.5 GeV/c.

The second Cerenkov counter, the high pressure counter, is subdivided into 12 optical cells. The average number of photoelectrons produced by a $\beta \sim 1$ particle is 20. This allows pion/heavy particle separation for $1.5 < p_{lab} < 5.5$ GeV/c. After appropriate cuts the identified heavy particle sample is quite clean, whereas the pion sample has a contamination of heavier particles of $\sim 1.5\%$, mainly due to overlapping γ -conversions from π^0 decays.

The third Cerenkov counter is an atmospheric pressure counter consisting of 18 optical cells. The average number of photoelectrons for a $\beta \sim 1$ particle is ~ 10 . Together with the high pressure counter it provides pion, kaon and proton separation for $p_{lab} > 5.5$ GeV/c.

Copper calorimeters placed behind the atmospheric pressure counters cover 1/7 of the solid angle of these counters. They were installed to provide a cross-check of the momentum measurement at $p_{lab} > 8$ GeV/c and were used in the trigger for part of the data sample.

Two sets of proportional wire chambers placed between the Cerenkov counters cover the same solid angle as these counters.

Interactions resulting in the production of a high p_t charged particle within the solid angle of the Cerenkov counters were selected using a three level trigger. The first level uses a scintillator hodoscope surrounding the beam pipe together with groups of wires in the proportional wire chambers to require $p_t > 0.8$ GeV/c. The second level uses hits in individual wires of the proportional wire chambers, and the third level uses a microprocessor operating on the appropriate drift chamber signals. For details see ref. 8.

The events were first processed through the AFS drift chamber reconstruction and fitting programs (ref. 9). Events were accepted if they contained a reconstructed primary vertex, a condition fulfilled by 99% of the events. Cuts were imposed on the tracks to ensure that they belonged to the event and that their momenta were reasonably well determined. All tracks were transformed to the centre of mass system, using the pion mass if not identified. Cuts on associated particles restricted them to be within 0.8 in rapidity and in the range $0.3 < p_t < 5$ GeV/c. No correction have been applied for the gaps up and down in the drift chamber or for a somewhat reduced acceptance for $|y| > 0.6$. Also no corrections have been applied for a reduced efficiency for tracks crossing the trigger track. That loss was found to be $\sim 15\%$ inside an angle of 10° to the trigger track. Data were collected with both polarities of the magnetic field. No significant differences were found for different magnet polarities. The acceptance of the associated particles is thus charge independent. Tracks within the acceptance of the Cerenkov counters were refitted using both drift chamber information and the reconstructed space points in the proportional wire chambers. This procedure served to reject false high p_t tracks, to reject particles interacting in the material of the Cerenkov counters and to improve the momentum resolution to approximately $\Delta p/p \sim 10\%$ at $p = 10$ GeV/c.

The sample contains 91300 events out of which 75500 have a trigger particle identified as π (52750 triggers) or heavy (22750 triggers) with $p_t > 3.0$ GeV/c and a mean p_t of 4.1 GeV/c. 3000 heavy triggers are separated into kaons and protons for p_{lab} above 5.3 GeV/c and the aerogel Cerenkov counter marks another 1600 heavy triggers as kaons in the p_{lab} range of 2 to 3.5 GeV/c.

40000 associated tracks in the Cerenkov arm are identified as pions (9000 by the aerogel counter), 1600 as kaons and 1800 as protons leaving 23000 unidentified tracks within the Cerenkov arm. Outside the acceptance of the Cerenkov arm the events have in the mean 2.8 tracks with a $p_t > 3$ GeV/c in the drift chamber.

3. Particle ratios

Figs.2 and 3 show as a function of p_t for positively and negatively charged particles, respectively, the fractional composition of the trigger particle flux into pions and heavier particles for $p_t < 5$ GeV/c and into pions, kaons and protons for $p_t > 5$ GeV/c. The ratios are averages over the c.m.s polar angle interval from 45° to 135° with $\langle \theta \rangle = 90^\circ$ and $\langle 1/\theta - 90^\circ \rangle \sim 20^\circ$. Within our statistics we see no variation in the ratios with θ . For comparison we also show in Figs. 2 and 3 the ratios (between invariant cross sections) measured by the CDHW collaboration (ref. 5) at $\langle \theta \rangle = 50^\circ$, and the extrapolation of the fit of the data at lower p_t and/or lower s from the BS collaboration (Table 4 in ref. 4)

The ratios have been corrected for contamination of the pion sample by heavier particles (a correction to the ratios of 1.5% for $p_t < 5$ GeV/c), for nuclear absorption and decays (corrections of 0.5 - 3%) and for a slightly worse acceptance for protons than for pions and kaons at $p_t > 5$ GeV/c (corrections about 1%). The errors on Figs.2 and 3 are statistical errors only. The systematic errors are estimated to be everywhere less than the statistical errors.

For positively charged particles we find the same fraction of π^+ ratio as the CDHW collaboration over the whole p_t range. For negatively charged particles the fraction of π^- is again equal at $p_t < 5$ GeV/c but we do not observe the rise in this fraction found by the CDHW collaboration at higher values of p_t . This difference may be an indication that heavy negatively charged particles are more centrally produced than negatively charged pions at high p_t .

The Lund model with the choice of parameters given in ref. 6 does not reproduce the data very well. In the model the ratios are independent of p_t over the range from 3 GeV/c to 7 GeV/c giving the ratios 0.7, 0.15, 0.15 for π^- , K^- , p and the ratios 0.65, 0.175, 0.175 for π^+ , K^+ , p.

4. Charge compensation vs rapidity.

We will now investigate how the charge of a high p_t particle in the trigger side jet is compensated in different regions of the phase space. A similar study has been performed by the CDHW collaboration at the CERN ISR (refs. 1a and 1b). Here we will study the charge compensation along an axis given by the direction of the trigger side jet. Our approach follows that given by the TASSO (ref. 10) and PLUTO (ref. 11) collaborations at PETRA.

The trigger side jet axis is found by a jet algorithm (ref. 12) using the charged particles with $p_t > 0.3$ GeV/c. This axis is, within a few degrees, given by the trigger particle direction. We define an asymmetry $A(y,y') = 2P(y,y') - 1$ where $P(y,y')$ is the probability of finding opposite charges for two given particles located at rapidities y and y' along the jet axis. For zero charge compensation P is equal to 0.5 and A is zero. We will study the quantity:

$$\bar{A}(y) = \frac{\int_{-2}^5 A(y,y') * q(y,y') dy'}{\int_{-2}^5 q(y,y') dy'}$$

which is obtained by weighting the asymmetry $A(y,y')$ with the two particle density $q(y,y')$ and averaging over all fast particles i.e. in the rapidity interval $-2 < y' < 5$. An equivalent expression of the function $\bar{A}(y)$ is

$$\bar{A}(y) = \frac{\int_{-2}^5 q(y,y')_{\text{opp. charge}} - \int_{-2}^5 q(y,y')_{\text{same charge}} dy'}{\int_{-2}^5 q(y,y') dy'}$$

$\bar{A}(y)$, ranging between -1 and +1, measures the strength of the charge compensation which acts between the the average pair of particles, the fast particle at y' and the other one at y .

4.1. Fast particles identified as pions and as heavies

Fig.4 shows the general behaviour of the charge compensation as a function of rapidity along the jet axis, for all negative and positive particles disregarding their identity. There is a strong short range correlation and a much weaker

long range correlation: both are stronger for fast particles of negative charge. However, the charge compensation when the second particle is a pion has the same strength for both charges of the fast particle, Fig.5a, but a clear difference in charge compensation is seen where the second particle is heavy particle (h), see Fig.5b. In Fig.6 we require that both the fast particle and the other is identified as π or heavy particle. We see some interesting effect: fast π^+ particles show much less short range charge compensation by h particles than fast π^- particles. Fast h^- particles have stronger charge compensation by other h particles than fast h^+ particles.

The interpretation of these effects follows a naive model of quark fragmentation. First we discuss fast π charge compensation by h particles, the majority of which are K mesons. A fast π^+ contains often a leading u quark which has been combined with a d quark from a dd quark-antiquark pair creation. The d quark can then combine with an s from an ss quark-antiquark pair creation to form a K_0 (it cannot form a K^-), close to the π^+ in rapidity which prevents a short range compensation by K mesons to the π^+ . On the other hand, a fast π^- (du) can get a K^+ (us) as a close partner giving rise to a short range effect. Other short range effects come from resonance production but these should be completely symmetric for the π, K case.

The stronger charge compensation for K^-K^+ (leading K^-) than for K^+K^- (leading K^+) could stem from the difference that while a K^+ (us) can be formed from a proton valence u quark from the interaction, the K^- contains no valence quark and will therefore be accompanied by one unit of both charge and strangeness. This apparently stronger charge compensation could also, to a large part, be explained by a general surplus of protons over antiprotons as we will see below.

4.2. Fast heavy particles separated into kaons and protons

With a more limited statistics we can separate the heavy particles into kaons and baryons. In figures 6e-j we show the charge compensation of kaons and baryons for a pion, kaon, and baryon fast particle. The kaon effect discussed above is not significant any longer.

We find that the charge compensation difference between positive and negative triggers for different species of associated particles mainly comes from a strong effect for associated baryons. The effect is clearly established against both pions and kaons and shows no dependence on rapidity which excludes a pure resonance effect (Δ^{++}). A simple interpretation is that there is a general surplus of protons relative to antiprotons uncorrelated with the trigger particle.

Using the Lund Monte Carlo (ref. 6) we have calculated what the Lund model predicts for these effects, see Fig. 7, and we see that the model is in general accordance with our data, however, the baryon behaviour is not very well reproduced.

5. Baryon-antibaryon effects

The Monte Carlo predicts a strong baryon-antibaryon correlation on the same side as the trigger, figure 7i, a fact which is not clear in the data, figure 6j, in the analysis of charge compensation as a function of rapidity. The difference between data and the model is better shown when we integrate the proton and antiproton production over the same (away) side as the trigger particle. We define the same (away) side by the azimuthal angle to the trigger particle, less than (larger than) 90° . In table 1 we give the proton/antiproton ratio for proton and antiproton triggers together with the results of Lund model calculations. The difference is now significant. The data do not give support to the dramatic change in this ratio between same and away sides as predicted by the model.

-
p/p ratio of associated particles

	data	Monte Carlo
proton trigger,same side particles	.9+- .3	.21+- .03
proton trigger,away side particles	1.4+- .4	.9 +- .1
antiproton trigger,same side	2.1+- .8	10.0 +-1.8
antiproton trigger,away side	1.1+- .3	1.5+- .2

Table 1.The ratio between associated production of protons and antiprotons for different sides in the event and different triggers.Monte Carlo calculations are done with the Lund model.

It is remarkable that the rate of low momentum protons and antiprotons does not depend on the trigger flavour ,see table 2.

	Associated protons	antiprotons per trigger
Pion trigger	0.087+- .001	.056+- .001
Heavy trigger	0.092+- .002	.065+- .002
p,p-trigger	0.079+- .008	.064+- .007

Table 2.Number of associated protons and antiprotons per trigger for different triggers.

6. Away side correlations

The charge compensation of trigger charge was seen to reach into the away side (long range effects). Usually the away side jet is balanced in azimuth (p_t plane) in an event with a high p_t trigger particle while the theta angle varies from event to event. Thus to study the away side we choose a variable containing p_t of the associated particles instead of rapidity with respect to the trigger-jet axis. These variables are $p_t(\text{ass})$, P_E and X_E :

$$P_E = \frac{-p_T(ass) * p_T(trig)}{p_T(trig)} \text{ and } X_E = \frac{P_E}{p_T(trig)}.$$

A particle is said to belong to the away side if $P_E > 0$.

We study charge compensation and charge ratio $R^{+/-}$ for unidentified away side particles in section 6.1 and for identified away side particles in section 6.2.

Charge compensation is here defined as the mean of $(N_{opp} - N_{same}) / (N_{opp} + N_{same})$ where N_{opp} (N_{same}) is the number of away side particles with opposite (same) charge as the trigger. $R^{+/-}$ is the mean of N^+ / N^- , the ratio of positive to negative away side particles.

In section 6.3 we study the away side correlations for two intervals of $p_T(ass)$, less and greater than 1.5 GeV/c and make comparisons on the charged density with ref. 2a.

Finally in section 6.4 we select different event configurations and compare our results with ref. 1a.

We make also comparisons with the Lund Monte Carlo (ref. 6) which is based on QCD and the Lund string model.

6.1. Unidentified Associated particles

Fig 8a shows the charge compensation on the away side vs P_E for positive and negative triggers whereas Fig. 8b shows the related charge ratio $R^{+/-}$ vs P_E . The correlation grows with P_E and is similar for both trigger charges but with an overall larger positive excess for negative triggers. Just as was found in the case with charge compensation vs rapidity we find the low P_E particles to be influenced by the trigger charge. The larger levels of $R^{+/-}$ or absolute value of charge compensation for negative than for positive triggers at low P_E is statistically significant. For leading away side particles we see that P_E is a more sensible

variable than rapidity. The clear rise of $R^{+/-}$ or the absolute value of charge compensation with increasing P_E is in agreement with the picture that the leading particle more often contains a scattered u valence quark. With the triggers unidentified the $R^{+/-}$ at highest values of P_E seems to get closer to each other for positive and negative triggers.

The parameter P_E is chosen because the $R^{+/-}$ distribution seems to be rather independent on trigger p_t (in our p_t range 3 - 8 GeV/c) when expressed versus P_E (Figs. 9a and 9b). Further no significant variation of $R^{+/-}$ with the trigger theta direction is found (Fig. 9c). (See also section 6.3 about theta dependence).

Simulation using the Lund model gives much weaker correlations, see Fig. 8c.

Studying the charge ratio for identified triggers π and h , we find at low P_E only a charge dependence. At high P_E π^- , π^+ agree within errors while h^- have a larger $R^{+/-}$ (Figs. 10a and 10b), whereas h^+ have a smaller value. Below we give the $R^{+/-}$ ratio for particles with P_E above 1.6 GeV/c.

π^-	1.34 +- 0.05	π^+	1.27 +- 0.05
h^-	1.51 +- 0.10	h^+	1.17 +- 0.06

We study this topic further in section 6.3.

To compare our $R^{+/-}$ distributions with π^0 triggered data (ref. 13) we must use X_E . Two $p_t(\text{trig})$ intervals are shown (Figs. 11a and 11b). The π^0 data falls roughly in the middle between our positive and negative trigger data in both cases, at least at low X_E again indicating the trigger side charge correlation to extend from the trigger side into the away side. At high X_E the $R^{+/-}$ could overlap for the three triggers (charged or neutral pions) consistent with the simple idea of scattered charged partons being predominantly u quarks.

Correlations between a high p_t trigger and charged particles on the away side have been studied by, for example, the BFS (ref. 2a) collaboration at essentially the same c.m.s. energy as we, using the SFM detector. They study a quantity $R_c \sim N_{\text{opp}}/N_{\text{same}}$ vs p_x of the associated particles mixing π^+ triggers with π^- triggers at 90° and finds a rather constant value $R_c = 1.1 - 1.2$. We study $R^{+/-}$ for different trigger charge separately but if also mixed as in ref. 2a we find the same result.

The CDHW collaboration (ref 1a) studies $R^{+/-}$ for different event configurations. We will compare to them in section 6.4.

At lower energy away side correlation studies have been done at FNAL with p on Beryllium, eg Bromberg et al (ref. 14). They observe a equally strong charge correlation $R^{+/-} \approx 2$ for π^- and h^- triggers for $p_t(\text{trig}) \approx 2$ GeV/c and $p_t(\text{away particles}) > 0.4 p_t(\text{trig})$. They see no correlations with positive triggers.

6.2. Identified Associated particles

Particle identification using dE/dx in the central detector at low momentum separates π , K and p. Plots of $R^{+/-}$ vs P_E for these show π and p to be significantly different but with little dependence on trigger flavour, see figure 12. The $R^{+/-}$ is stronger correlated with trigger charge for away side p than away π .

On the other hand for away side K there is an interesting effect: $R^{+/-}$ for h^- triggers is significantly larger than for π^- triggers. π^+ and h^+ triggers give roughly equal charge ratio for away K, see Figs. 12. To interpret this effect we consider the h^- as being a K^- . Then the correlation could come from a decay $X \rightarrow K^+ K^-$ but then it should be present for h^+ triggers as well. An invariant mass plot contains no significant signal. We thus interpret this effect in the same way as above where we used rapidity, which in this case

means that the fragmentation giving rise to a leading K^- on the trigger side will in some cases produce a K^+ which can be found on the away side.

At lower energy away side correlation studies have been done at FNAL with p on Beryllium, eg Fisk et al(ref. 15). They can identify π , K, p but see rather little dependence on trigger particle type ($p_t(\text{trig})$ is 3 to 4 GeV/c) and no significant excess of positive over negative for h^- triggers.

The Lund model produces the same features as seen in data at low P_E , and its prediction is included in figure 12. In the Lund model h^- triggers come more often from a fragmenting gluon (40%) than other triggers do (30%).

6.3. Charged density and charged ratios

The BFS collaboration, ref. 2a, finds an interesting effect not expected from lowest order QCD: a correlation between negatively charged heavy triggers and positive away side particles with $p_t > 1.5$ GeV/c (a 3 sigma effect). We have seen above an indication of such an effect in our data and in view of the physical interest of this effect we will do a detailed comparison with the BFS analysis.

The effect seen in ref. 2a is a larger excess of positive over negative large p_t away side particles for h^- triggers than for other triggers. We divide the away side particles into two p_t intervals, $p_t < 1.5$ and $p_t > 1.5$ GeV/c.

Events with tracks fulfilling the following requirements were selected:

$$3.0 < p_t(\text{trig}) < 4.5 \quad (a)$$

$$|\phi(\text{trig}) - \phi(\text{associated})| > 150^\circ \quad (b)$$

The BFS group (ref. 2a) used these plus

$$y(\text{trig}) \sim 0 \quad (c)$$

$$p_t > 1.5 \quad (d)$$

Our distribution in θ direction of the trigger particles is rather flat for $|y| < 0.15$ and drops to 0 at $|y| \sim 0.8$.

Fig. 13 shows our mean charge density on the away side with restrictions a, b and d. The trigger theta is divided into $/\theta - 90^\circ/$ less, greater than 20° and all theta. There is certainly a tendency of increasing positive over negative excess with increasing theta except for π^- triggers. With $/\theta - 90^\circ/ < 20^\circ$ the largest excess is seen for h^- triggers in accordance with ref. 2a, and we confine ourselves to this theta region from now on.

As in ref. 2a we present the charge density ratios h^-/π^- and h^+/π^+ , see Fig. 14a and 14b, where their data points for $p_t > 1.5$ GeV/c have been included. No special flavour dependence is seen for the lower p_t bin (Fig. 14a). For $p_t > 1.5$ GeV/c (Fig. 14b) positive density ratios agrees well with ref. 2a and negative density ratios agree within 2 sigma.

Below we compare the differences in density ratios of positive and negative associated particles with $p_t > 1.5$ GeV/c.

triggers	difference (pos - neg)		difference (BFS - AFS)
	BFS	AFS	
h^-/π^-	0.52+-0.17 3.1 sigma	0.225+-0.098 2.3 sigma	0.295+-0.196 1.5 sigma
h^+/π^+	-0.12+-0.12 1.0 sigma	0.004+-0.084 0.05 sigma	-0.124+-0.146 0.8 sigma

Table 3. Differences between density ratios of positive and negative away side particles with $p_t > 1.5$ GeV/c and a comparison of the differences with BFS (ref. 2a)

Thus we see a larger density ratio of associated positive than negative particles with $p_t > 1.5$ GeV/c with a 2.3 sigma significance. On the other hand we agree with BFS (ref. 2a) within 1.5 sigma on their excess of positive over negative density ratio for h^-/π^- triggers.

Further we find the charged density ratios for away side particles with $p_t < 1.5$ GeV/c to be compatible with no dependence, see Fig. 14a. For $p_t > 1.5$ GeV/c (Fig 14.b) the difference from one is larger, see table 4 below. The BFS data are compatible with one except the negative h^-/π^- ratio where they find a difference 0.42 ± 0.09 (4.8 sigma).

triggers	negative associated	positive associated
h^-/π^-	0.811 ± 0.068 (2.8 sigma)	1.036 ± 0.07 (0.5 sigma)
h^+/π^+	0.872 ± 0.062 (2.1 sigma)	0.876 ± 0.057 (2.2 sigma)

Table 4. The charge density ratio for negative and positive away side particles.

The ratio $R^{+/-}$ of away side particles with $p_t > 1.5$ GeV/c and using the other cuts in this section are the following:

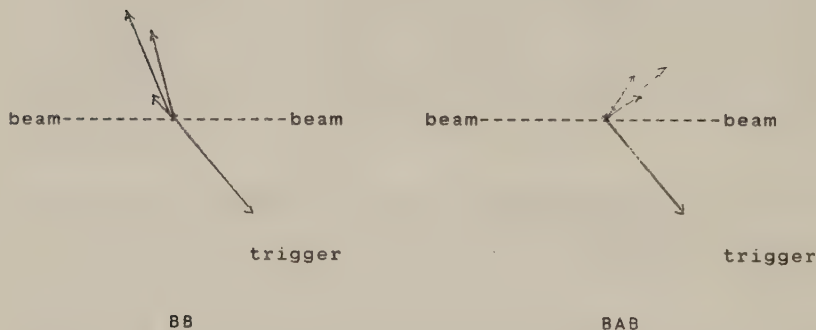
π^-	1.288 ± 0.066	π^+	1.199 ± 0.063
h^-	1.646 ± 0.152	h^+	1.205 ± 0.095

We see that positive and negative pion triggers give the same $R^{+/-}$ within errors, as seen in section 5.1. This indicates that for pion triggers the hard scattering is flavour independent. Positive heavy triggers gives the same value, whereas in the total sample we had an indication of a difference from the pion triggers. Negative heavy triggers, however, has a $R^{+/-}$ markedly larger than the others.

A simulation with the Lund model using our cuts does not reproduce the h^- effect (see Figs. 14a and 14b where MC points are included)

6.4. Studies of event configurations

The CDHW collaboration ,Ref. 1a, trigger at 50° and they select events of two configurations, back to back (BB) and back to antiback (BAB).



They find much larger charge ratio $R^{+/-}$ for h^- triggers than π^+ triggers in BAB events and no difference in BB events. Because the gluons tend to carry a lower fraction of the proton momentum than the quarks the scattering angle between quark and gluon would be smaller than between quark and quark (or between gluon and gluon) and we expect the BB configuration to be dominated by quark-quark scattering and the BAB configuration to be dominated by quark-gluon scattering. The CDHW collaboration explains their findings as due to the charge difference between quarks and gluons. In spite of our limited theta acceptance we try a similar analysis.

Our trigger theta distribution is rather central, symmetric around $\theta=90^\circ$. The smallest theta we can use with sensible statistic is 70° to the beams with a mean θ of 61° . In that case we get 2,188 BB and 2,286 BAB events. We chose events with $P_{E\text{max}}$ greater than 1 GeV/c and call an event BB(BAB) if the $P_{E\text{max}}$ particle and the trigger were in the opposite(same) hemispheres with respect to $\theta = 90^\circ$ plane.

We find $R^{+/-}$ to depend only on trigger charge, not on neither trigger flavour nor on event configuration (Fig. 15). Our $R^{+/-}$ values are smaller generally than those of ref. 1a, see Fig. 16, where we compare our π^+ and h^- trigger data for all theta directions, with the BB configuration of ref. 1a.

Our mean trigger theta is only somewhat larger than that of ref. 1a so we believe the different results to be due to our acceptance, being limited to the central region.

Again, simulating events with the Lund model using our detector acceptance reproduces the $R^{+/-}$ values and the P_E dependence we observe. There is no difference between BB and BAB configurations in this model.

7. Conclusions

The composition of the charged particle flux around $\theta = 90^\circ$ in the c.m.s has been measured in pp collisions at the energy $\sqrt{s} = 63$ GeV for transverse momenta up to 8 GeV/c. In the p_t range from 5 GeV/c to 8 GeV/c we find the π^+ , K^+ , p compositions to be about 0.63, 0.24, 0.13 and the π^- , K^- , p composition to be about 0.73, 0.16-0.20, 0.10-0.05 (Figs. 2 and 3).

For the charge correlations between high p_t identified particles and associated particles we find:

The charge compensation on the same side as the trigger depends strongly on the identity of the associated particles and on the identity of the trigger particle. The compensation follows qualitatively a simple picture of quark fragmentation but superimposed by low momentum protons uncorrelated with the fast particle and the effects are generally reproduced in the Lund Monte Carlo model of pp collisions. However, the model has difficulties with baryon effects, and in particular the production of low momentum baryons and antibaryons is not reproduced.

The charge structure of unidentified particles on the away side is found to be influenced by trigger charge: the charge ratio of low p_t awayside particles is significantly larger with negative than with positive triggers but independent on trigger flavour. The charge ratio grows with p_t of the associated particles for both trigger charges. There is further an indication of larger excess of positive over negative high p_t particles on the away side when the trigger is a negative heavy particle, an effect not expected from lower order QCD and formerly found by the BFS collaboration. The ratio of positive to negative awayside large p_t particles is the same for positive and negative pion triggers indicating a flavour independent parton scattering in that case. The Lund model reproduces essentially the features of our data on the away side except for the production of high momentum associated particles.

8. References

Ref. 1

a) CERN-Dortmund-Heidelberg-Warsaw Collaboration CERN/EP 82-184.

b) CERN-Dortmund-Heidelberg-Warsaw Collaboration CERN/EP 82-212.

Ref. 2

a) British-French-Scandinavian Collaboration M.G. Albrow et al, Nucl.Phys. B145, (1978) 305.

b) British-French-Scandinavian Collaboration M.G. Albrow et al, Nucl.Phys. B160, (1979) 1.

Ref. 3

a) R. Cottrell et al, Phys.Lett. 55B (1975) 341.

b) M. Della Negra et al, Phys.Lett. 59B (1979) 481.

c) D. Antreasyan et al, Phys.Rev.Lett. 38 (1977) 112.

Ref. 4

B. Alper et al, Nucl.Phys. B100 (1975) 237.

Ref. 5

D. Drijard et al, Nucl.Phys. B208 (1982) 1.

Ref. 6

H.-U. Bengtsson, LU-TP 82-15 and references given therein.

Ref. 7

a) H. Gordon et al, Nucl.Instr. & Methods 196 (1982) 303.

b) O. Botner et al, Nucl.Instr. & Methods 196 (1982) 315.

Ref.8

B. Heck et al, EPS Conf. on Computing, Bologna 1980.

Ref.9

S. Almeded and B. Lörstad, Comput.Phys.Comm. 27, 1981.

Ref.10

R. Brandelik et al, Phys.Lett. 100B (1981) 357.

Ref.11

C. Berger et al, DESY 82-058.

Ref.12

T. Sjöstrand, Comput.Phys.Comm. 27 (1982) 243.

Ref.13

T. Åkesson et al, Phys.Lett. 118B (1982) 178.

Ref.14

C. Bromberg et al, Phys.Rev.Lett 43 (1979) 561.

Ref.15

R. J. Fisk et al, Phys.Rev.Lett 40 (1978) 985.

Ref.16

A. G. Clark et al, Nucl.Phys.B160 (1979) 397.

9. Figure captions

Fig.1

The Axial Field Spectrometer in a view transverse to the collision axis. The magnetic coils are out of the paper plane. The left calorimeter wall is shown in a retracted position.

Fig.2

The fractional composition of the particle flux into pions, kaons and protons, as a function of p_t , for positively charged particles.

Fig.3

The fractional composition of the particle flux into pions, kaons and antiprotons, as a function of p_t , for negatively charged particles.

Fig.4

Compensation of charge, $\tilde{A}(y)$, of particles in the test interval $2 < y' < 5$ (fast particles) as a function of rapidity along the jet axis.

- fast negative particles,
- x fast positive particles.

Fig.5

Charge compensation $\tilde{A}(y)$ by associated identified particles, as a function of rapidity y , of fast particles in the test interval $2 < y' < 5$.

- fast negative particles,
- x fast positive particles.

Fig.6

Charge compensation $\tilde{A}(y)$ by associated identified particles, as a function of rapidity y , of fast identified particles in the test interval $2 < y' < 5$.

- a. - fast π^- compensated by π^+ s.
- x fast π^+ compensated by π^- s.
- b. - fast h^- compensated by π^+ s.
- x fast h^+ compensated by π^- s.
- c. - fast π^- compensated by h^+ s.
- x fast π^+ compensated by h^- s.
- d. - fast h^- compensated by h^+ s.
- x fast h^+ compensated by h^- s.

Fig.7

Prediction by the Lund Monte Carlo for pp collisions of charge compensation $A(y)$ by associated identified particles, as a function of rapidity y , of fast identified particles in the test interval $2 < y' < 5$, as a function of rapidity, y .

- a. - fast π^- compensated by $\pi:s$.
 x fast π^+ compensated by $\pi:s$.
- b. - fast h^- compensated by $\pi:s$.
 x fast h^+ compensated by $\pi:s$.
- c. - fast π^- compensated by $h:s$.
 x fast π^+ compensated by $h:s$.
- d. - fast h^- compensated by $h:s$.
 x fast h^+ compensated by $h:s$.

Fig.8a

Charge compensation of positive and negative triggers vs P_E by unidentified away side particles. (o positive trigger, filled o negative triggers)

Fig.8b

Charge ratio $R^{+/-}$ vs P_E for unidentified away side particles with positive and negative triggers. (o positive triggers, filled o negative triggers)

Fig.8c

Charge ratio $R^{+/-}$ vs P_E for unidentified away side particles with positive and negative triggers in the Lund model. (o positive triggers, filled o negative triggers)

Fig.9a

Charge ratio $R^{+/-}$ vs P_E for unidentified away side ejm830les with positive triggers in three intervals of trigger p_t : 3 to 3.5 (filled o), 3.5 to 4.5 (o) and larger (x) than 4.5 (GeV/c).

Fig.9b

Charge ratio $R^{+/-}$ vs X_E for unidentified away side particles with negative triggers in three intervals of trigger p_t : 3 to 3.5 (filled o), 3.5 to 4.5 (o) 4.5 and larger (x) than 4.5 (GeV/c).

Fig.9c

Charge ratio vs P_E for unidentified away side particles with positive and negative triggers with p_t

larger than 3.0° GeV/c. Trigger θ direction in two intervals, $/\theta-90^\circ/$ less than 10° and larger than 20° .

Fig.10

Charge ratio vs P_E for unidentified away side particles for positive(o) and negative(filled o) identified triggers with p_t trigger larger than 3.0 GeV/c.

- a. Pion triggers.
- b. Heavy triggers.

Fig.11

Charge ratio vs X_E for unidentified away side particles for positive(o) and negative(filled o) triggers and π^0 (x) trigger data from ref. 13. Two intervals of the trigger p_t :

- a. Trigger p_t between 3 and 4.5 GeV/c.
- b. Trigger p_t larger than 4.5 GeV/c.

Fig.12

Charge ratio vs P_E for low momentum identified away side particles, π , K and p for identified positive and negative triggers with p_t larger than 3.0 GeV/c:

- a,b,c. Pion triggers.
- d,e,f. Heavy triggers.

Fig.13

Density of unidentified away side particles, with $p_t > 1.5$ GeV/c and $/\phi(\text{ass})-\phi(\text{trig})/>150^\circ$. The triggers are identified π and h particles with trigger p_t between 3.0 and 4.5 (GeV/c). The $\theta(\text{c.m.s})$ of the triggers is shown for $/\theta-90^\circ/$ less than (Δ) and greater than (square) 20° and for all theta(o).

Fig.14

Density ratios of unidentified away side particles with $/\phi(\text{ass})-\phi(\text{trig})/>150^\circ$. The triggers are identified π and h particles with trigger p_t between 3.0 and 4.5 (GeV/c). The $\theta(\text{c.m.s})$ of the triggers is shown for $/\theta-90^\circ/$ less and greater than 20° and for all θ :

- a. $p_t(\text{associated}) < 1.5$ GeV/c.
- b. $p_t(\text{associated}) > 1.5$ GeV/c.

Fig.15

Charge ratio vs P_E of unidentified away side particles in different event configurations with identified trigger particles with p_t larger than 3.0 and $/\theta-90^\circ/$ larger than 20° . The different event configurations are

explained in the text.

Fig.16

Charge ratio vs X_E of unidentified away side particles with π^+ and heavy-triggers for all trigger θ and $p_{t, \text{ of the trigger}}$ larger than 3.0 GeV/c together with π^+ and heavy-trigger data in the back to back configuration of ref. 1a

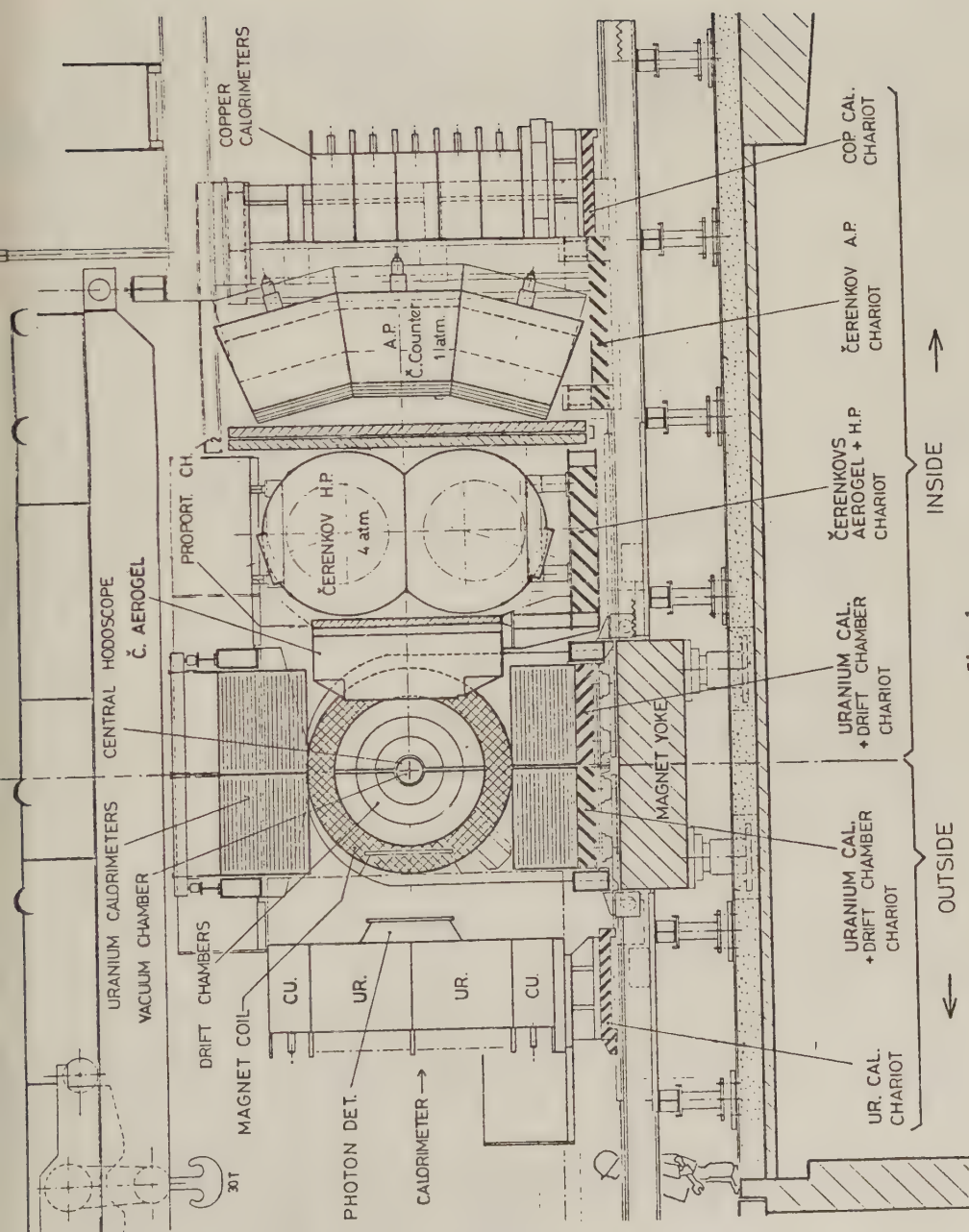


Fig. 1

Fig. 2

PARTICLE RATIO - POSITIVELY CHARGED PARTICLES

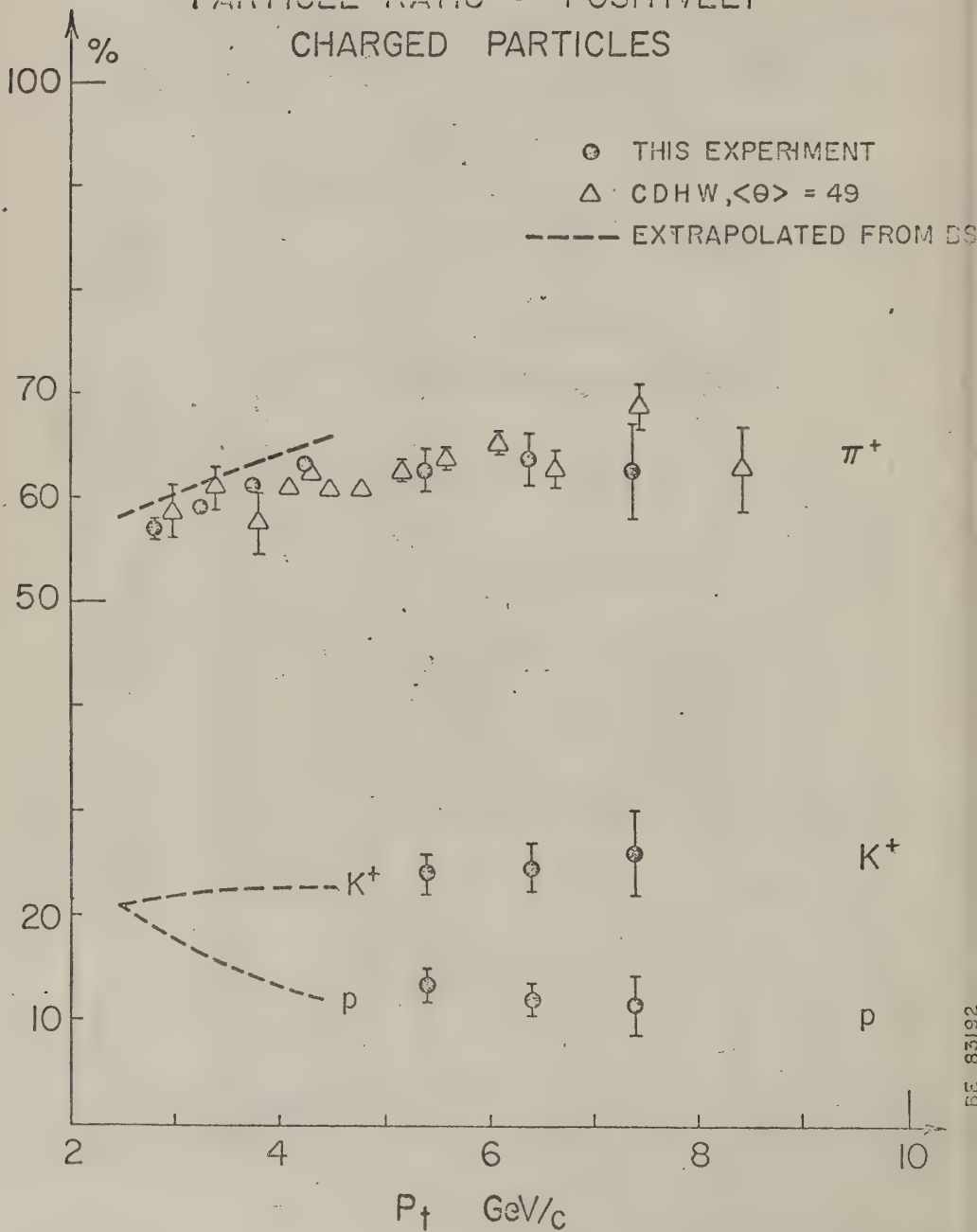
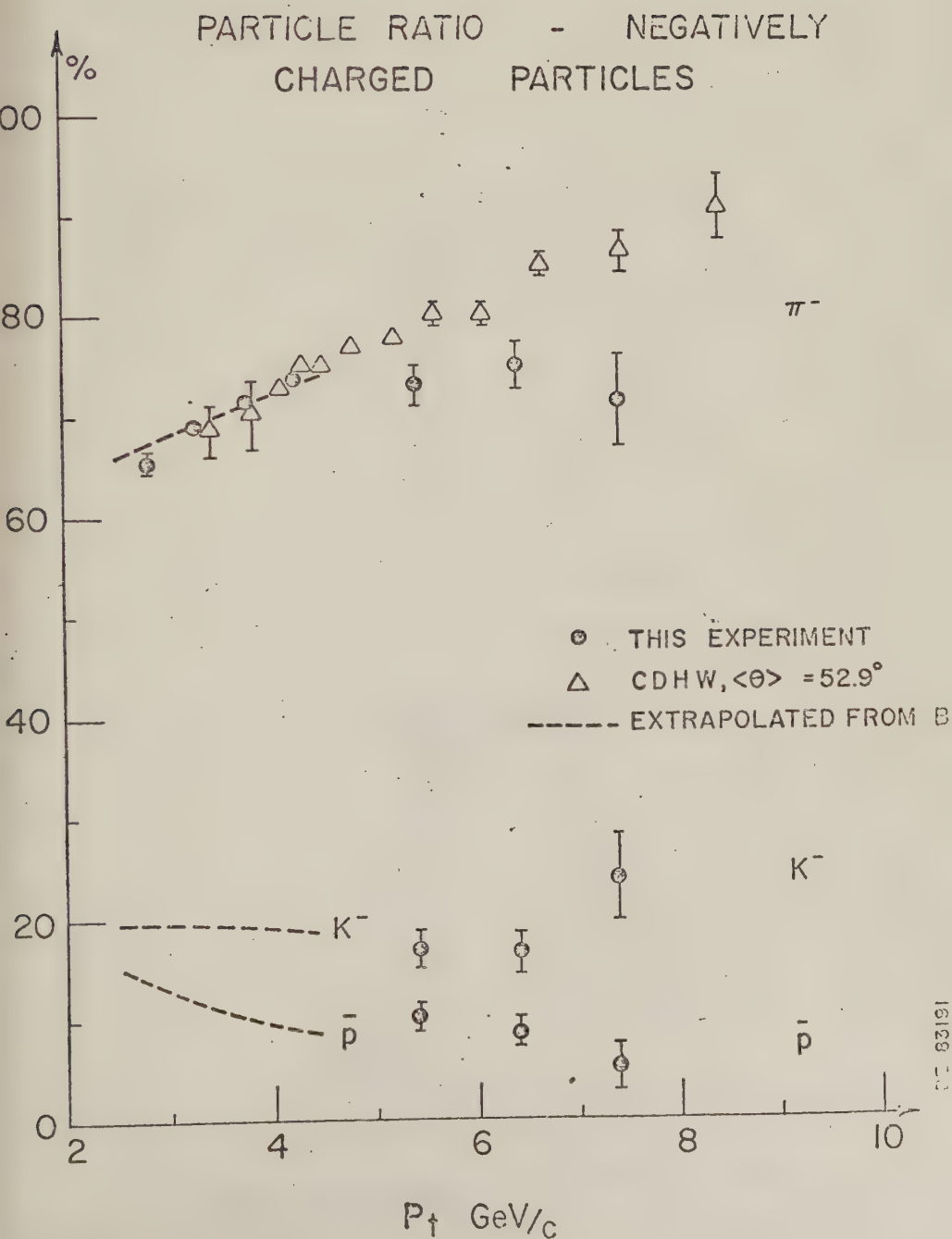


Fig. 3



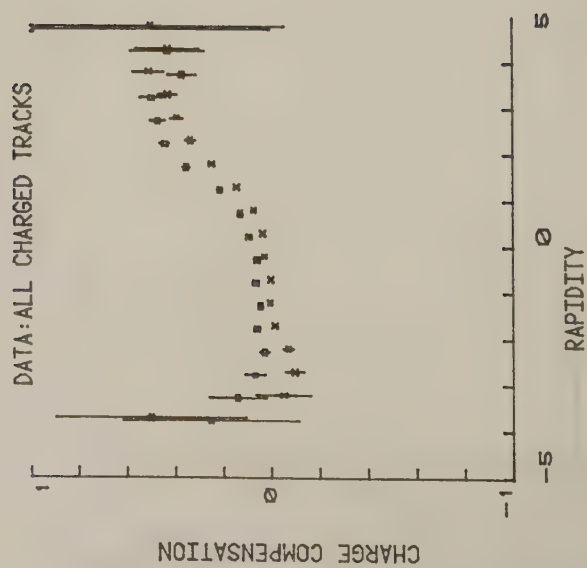


FIGURE 4

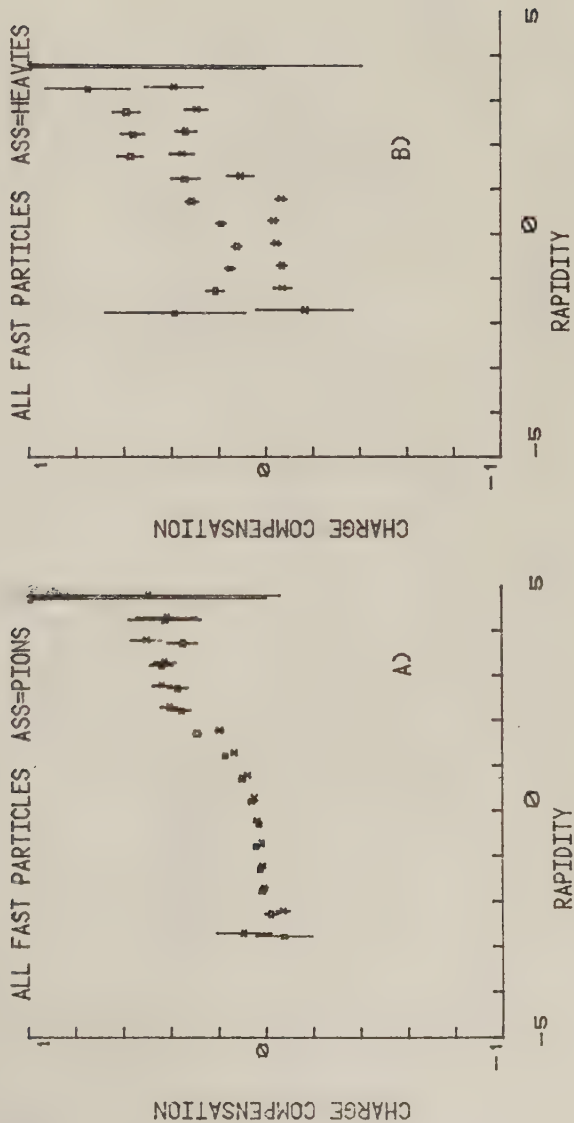


FIGURE 5

FAST PARTICLE = PION

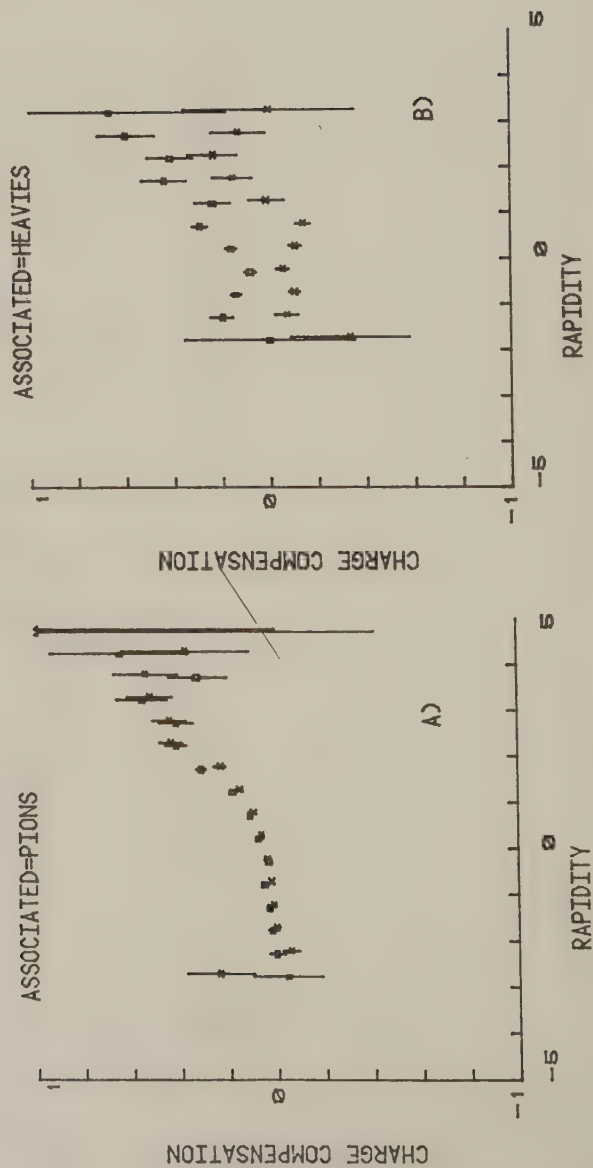


FIGURE 6

FAST PARTICLE = HEAVY

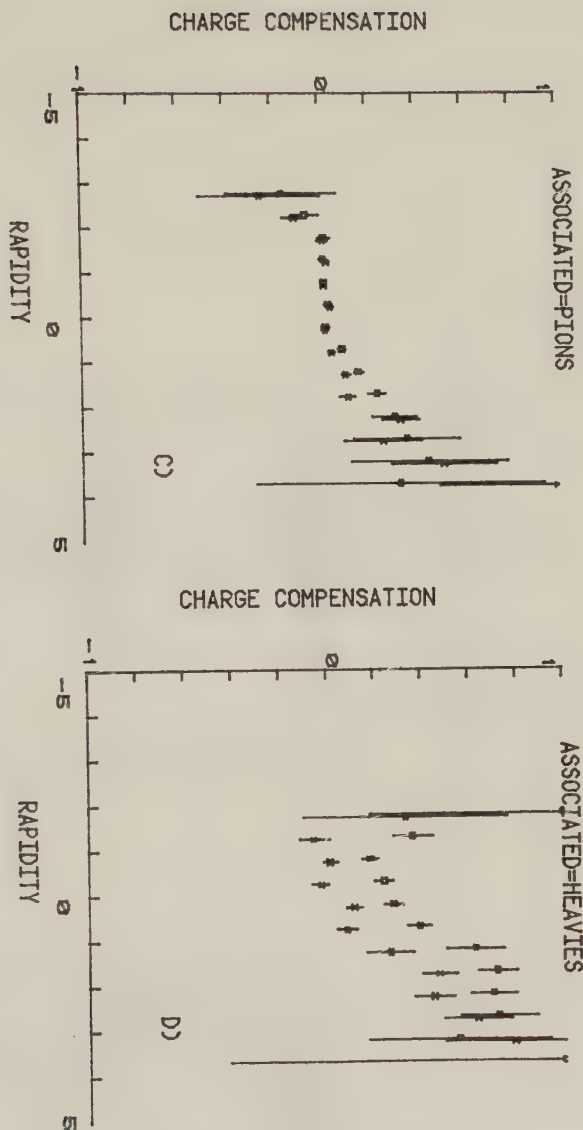


FIGURE 6

FAST PARTICLE = PION

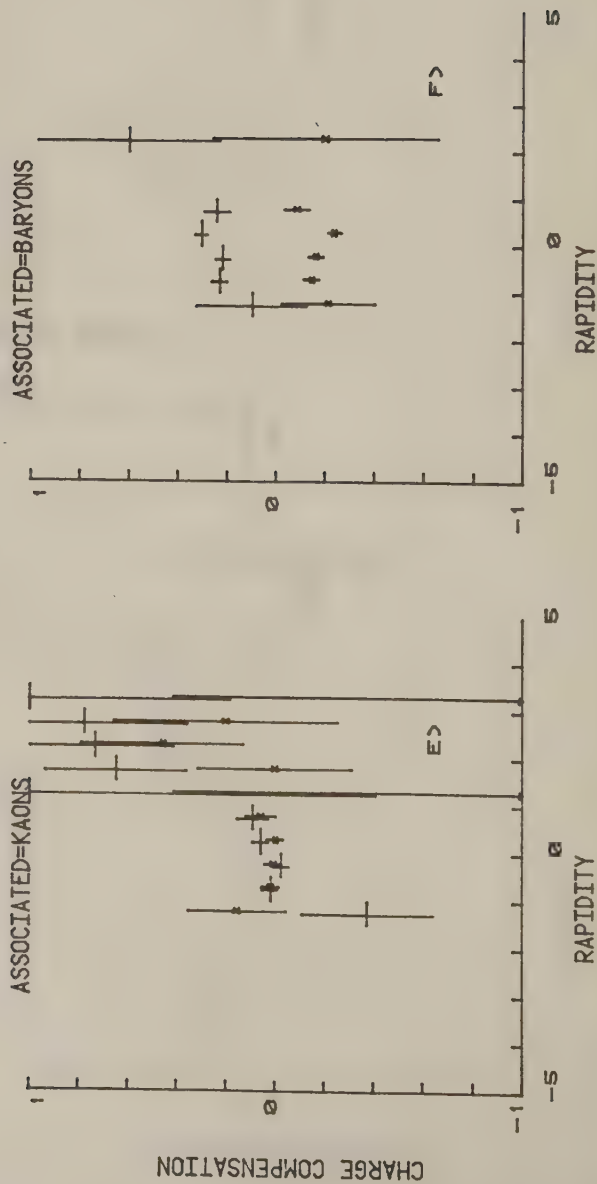


FIGURE 6

FAST PARTICLE = KAON

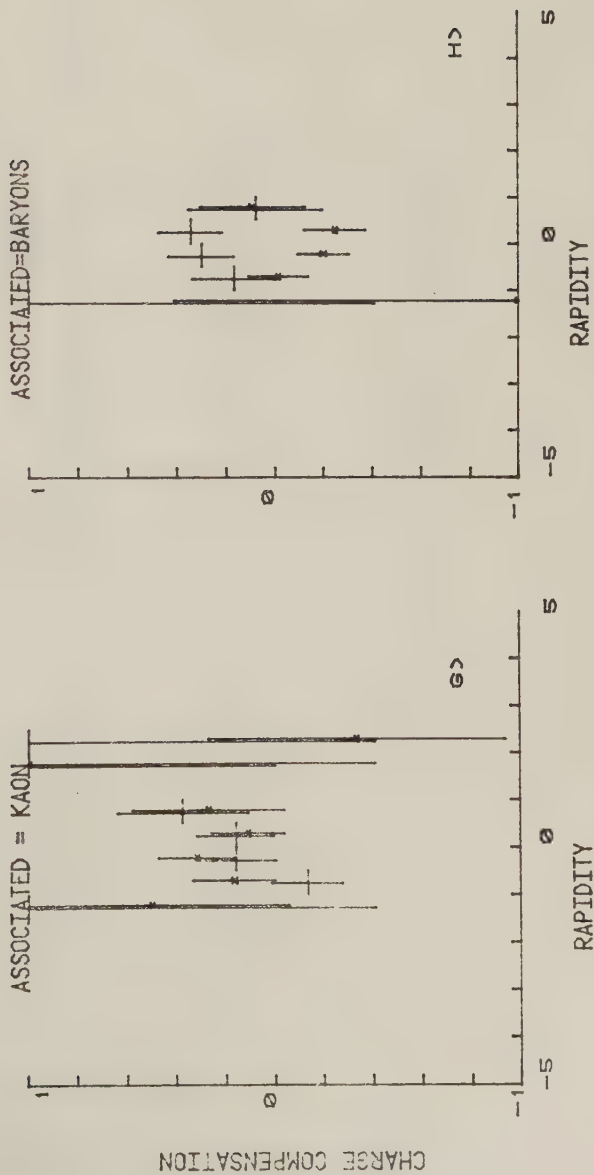


FIGURE 6

FAST PARTICLE BARYON

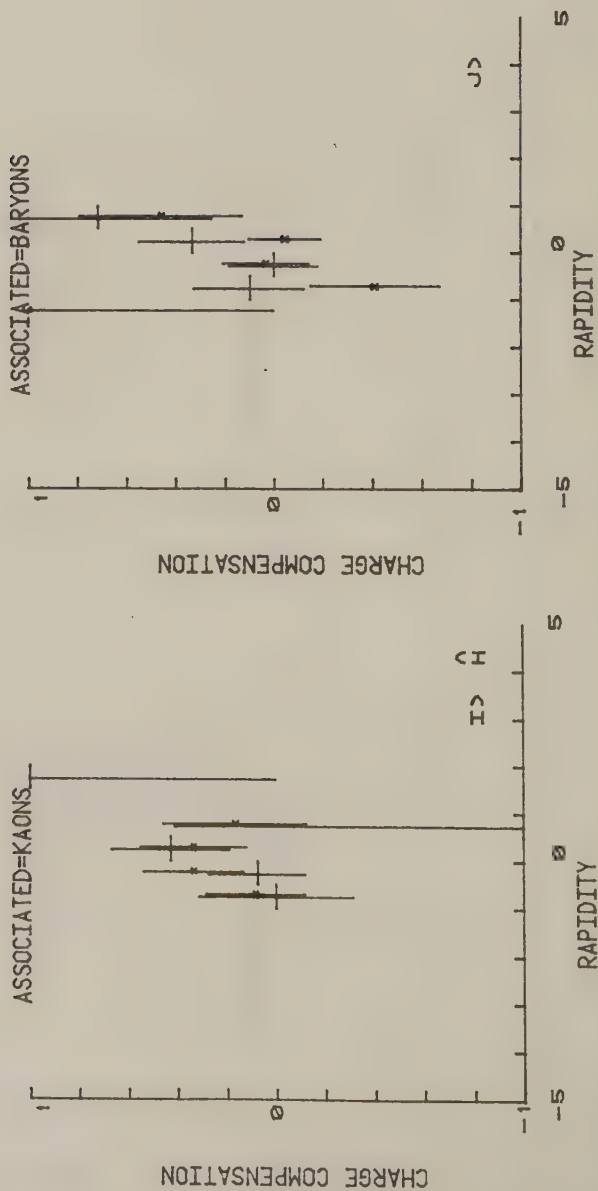


FIGURE 6

MONTE-CARLO.

FAST PARTICLE PICN

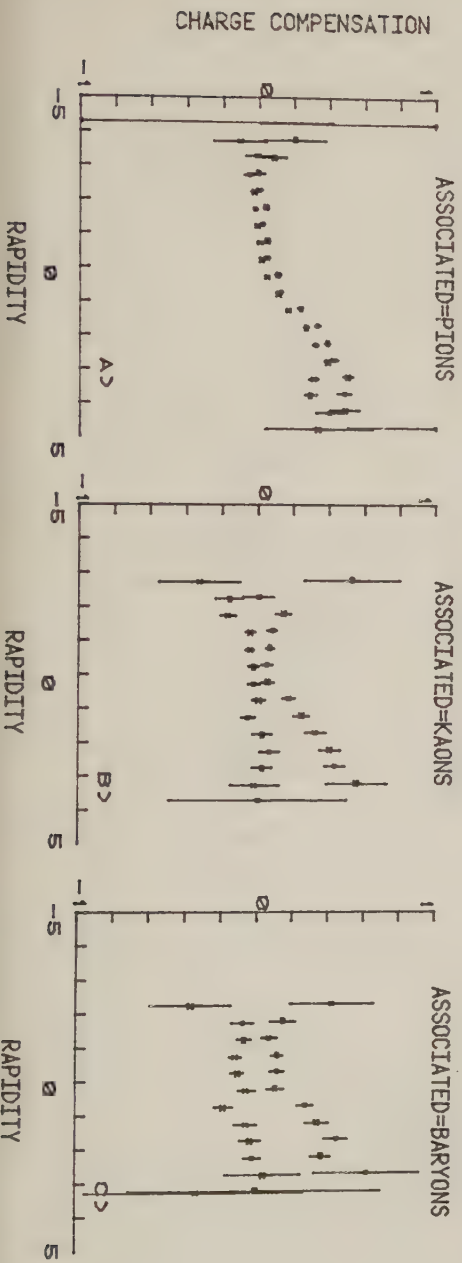


FIGURE 7

MONTE CARLO .

FAST PARTICLE KAON

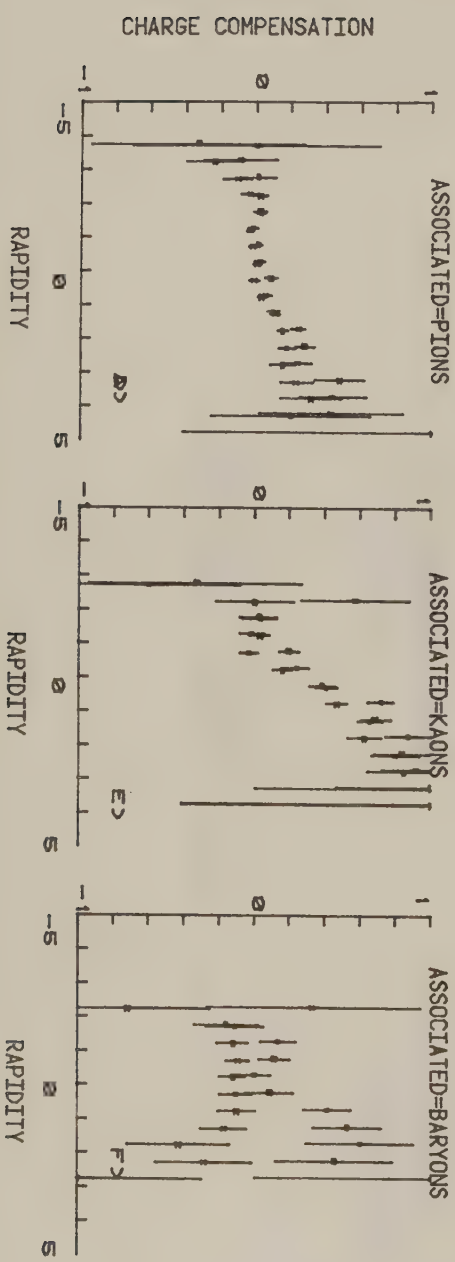


FIGURE 7

MONTE CARLO

FAST PARTICLE BARYON

CHARGE COMPENSATION

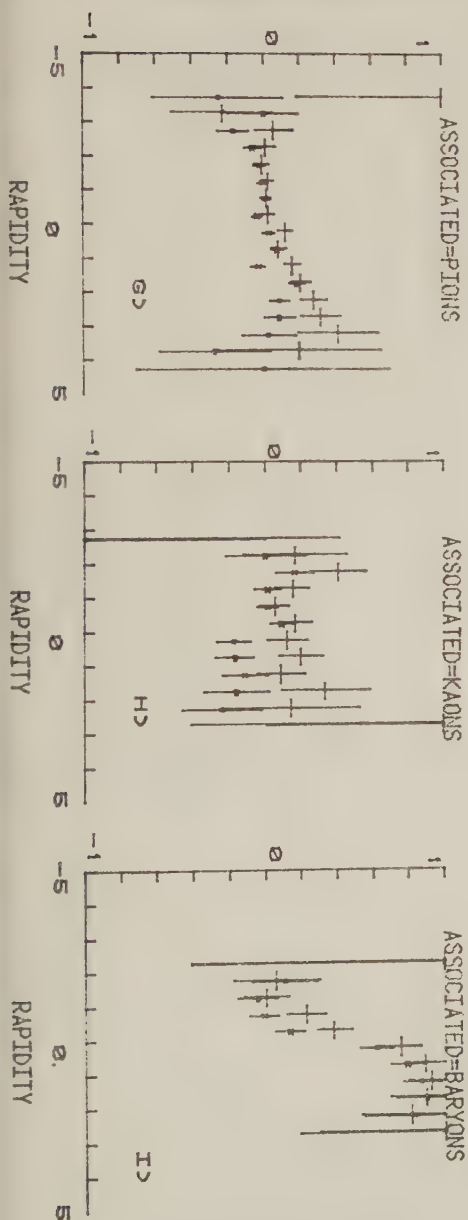


FIGURE 7

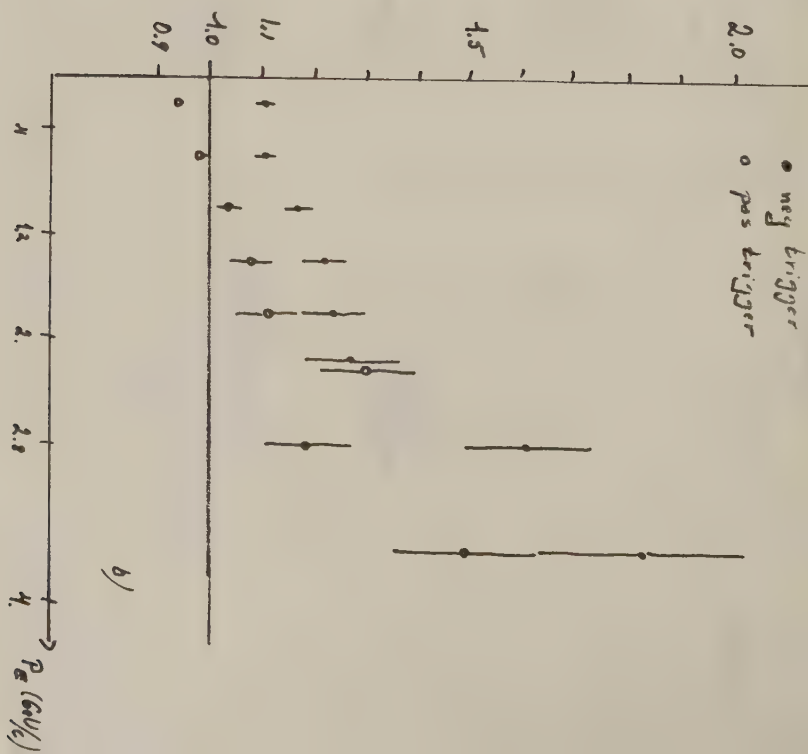
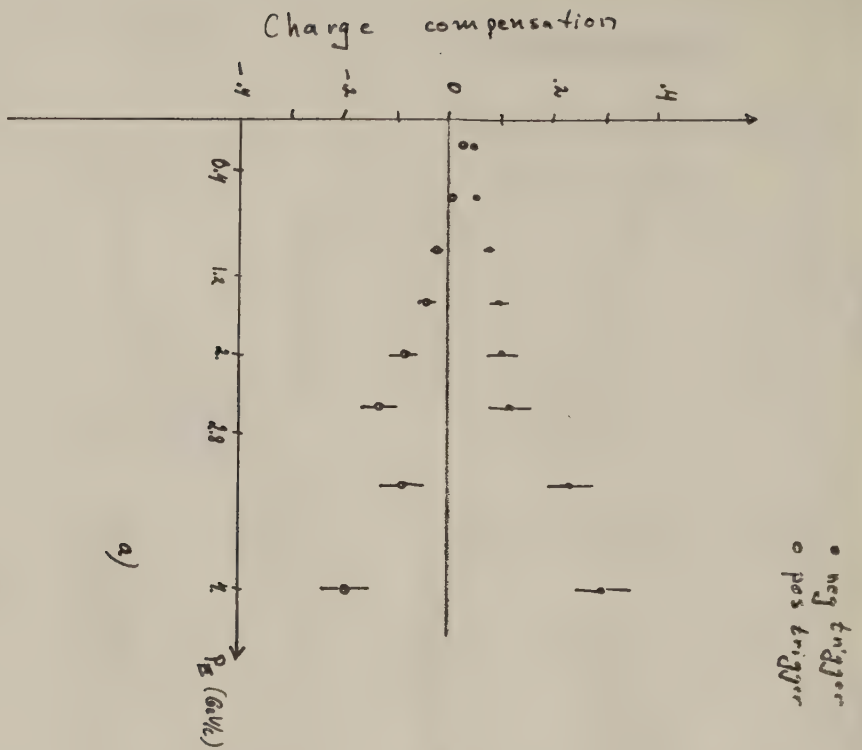


Figure 8

Monte Carlo

• neg trigger
○ pos trigger

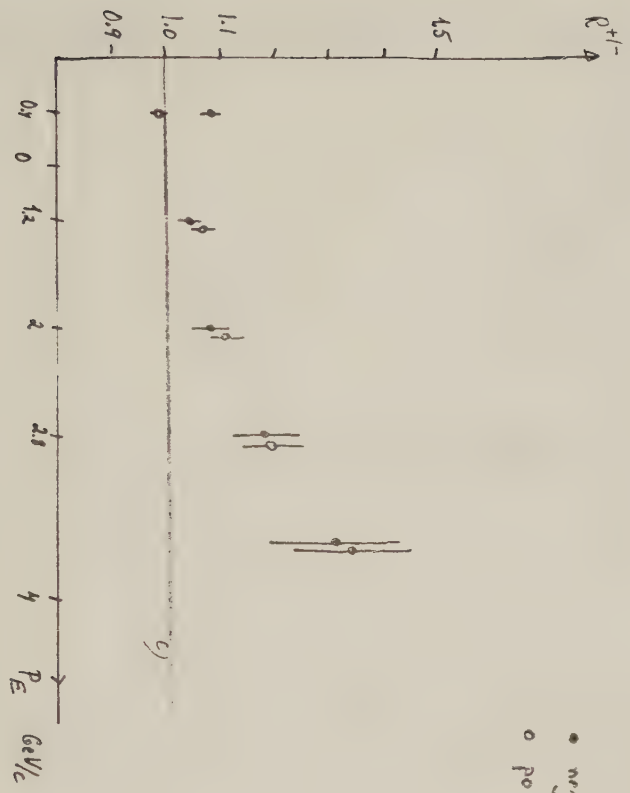


Figure 8

Positive triggers

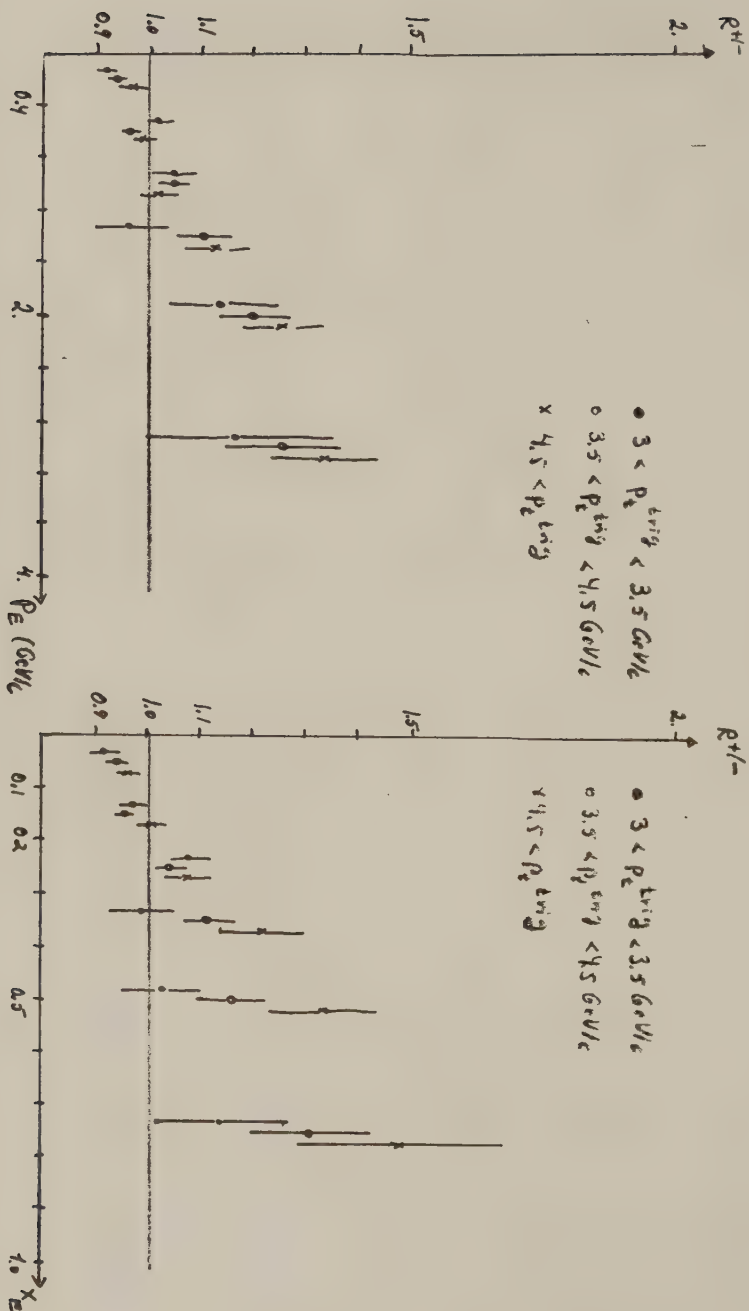
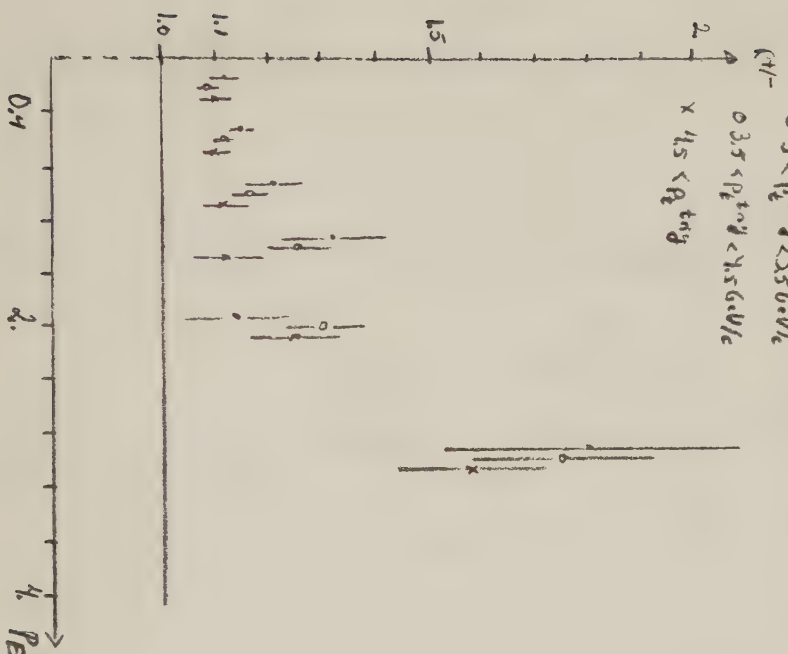


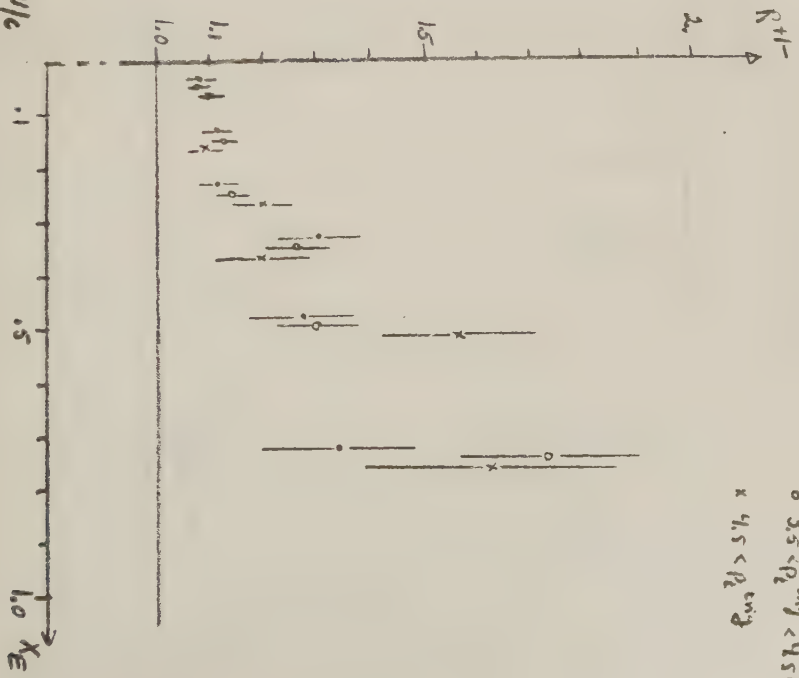
figure 9a

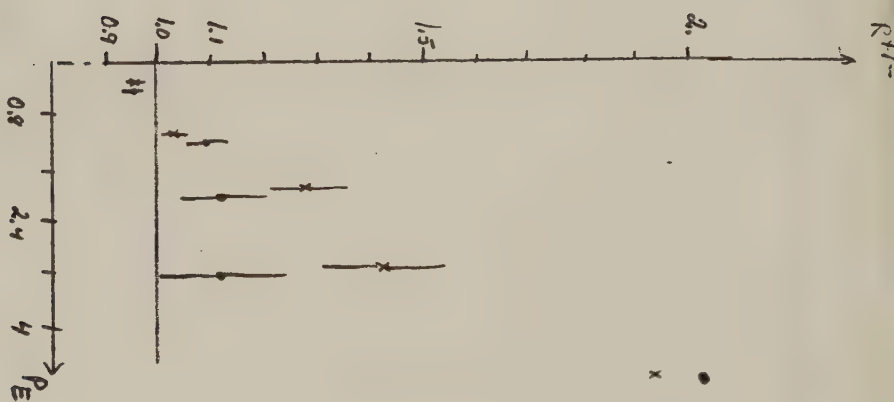
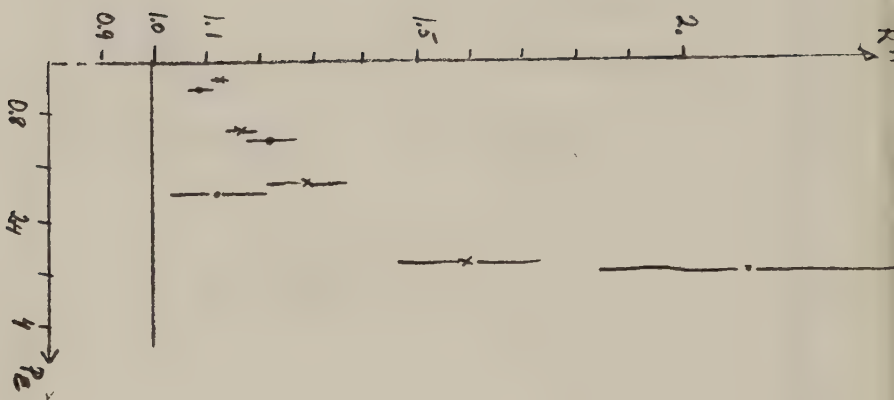
Negative triggers

$\bullet 3 < P_t^{neg} < 3.5 \text{ GeV/c}$
 $\circ 3.5 < P_t^{neg} < 4.5 \text{ GeV/c}$
 $\times 4.5 < P_t^{neg}$



$\bullet 3 < P_t^{neg} < 3.5 \text{ GeV/c}$
 $\circ 3.5 < P_t^{neg} < 4.5 \text{ GeV/c}$
 $\times 4.5 < P_t^{neg}$

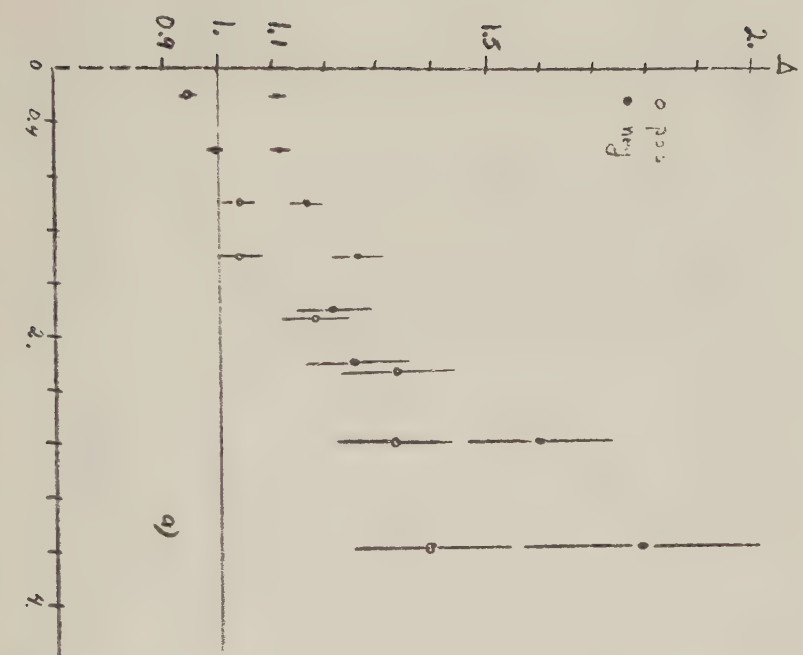




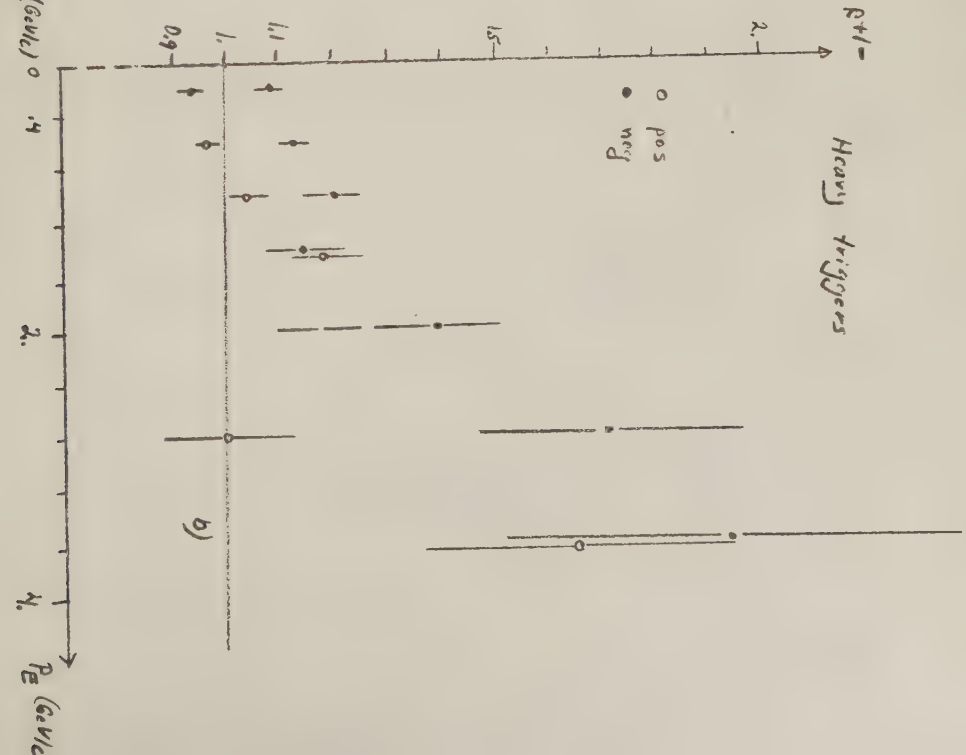
• $|\theta - 90^\circ| < 10^\circ$
 x $|\theta - 90^\circ| > 20^\circ$

figure 9c

K^{*1-} Pion triggers



K^{*1-} Heavy triggers



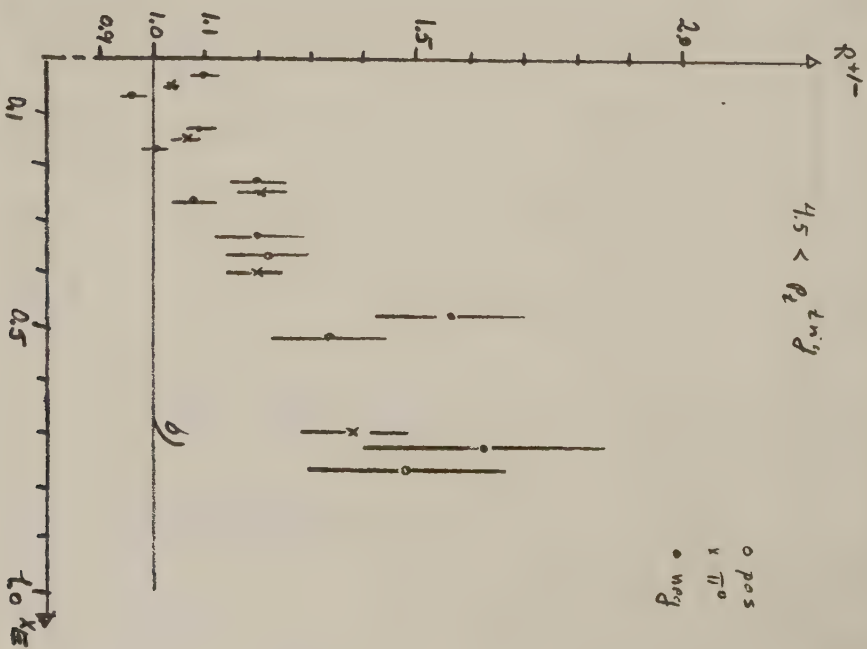
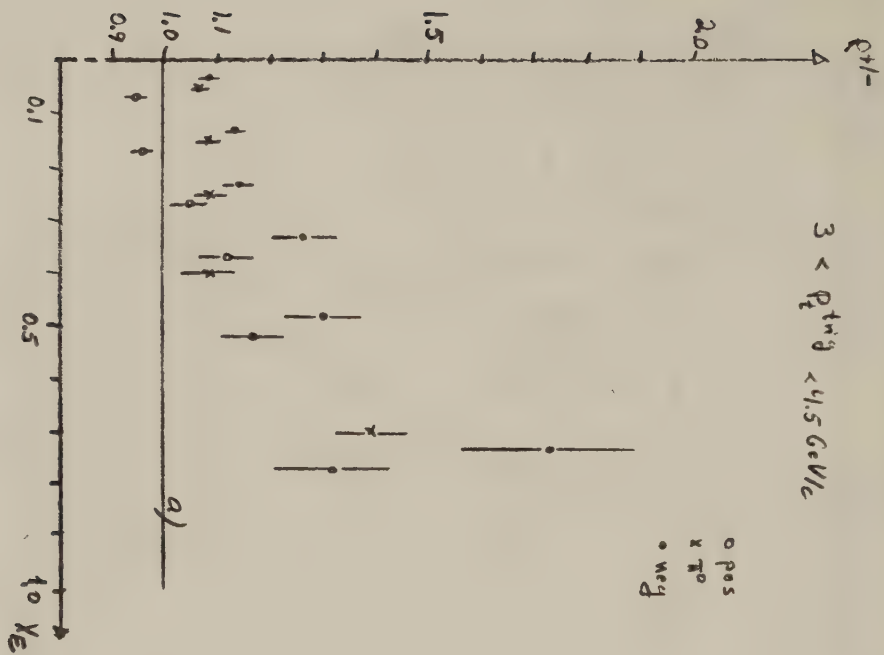
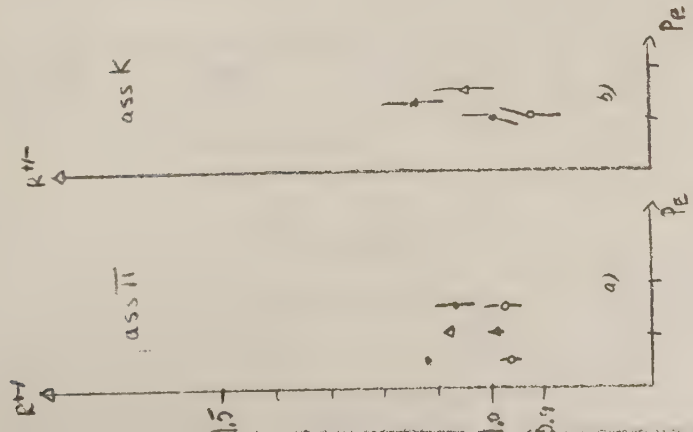


figure 11

triggers
 data { $\bullet$ neg $\circ$ pos
 MC { $\blacktriangle$ neg $\triangle$ pos

Pion triggers



Heavy triggers

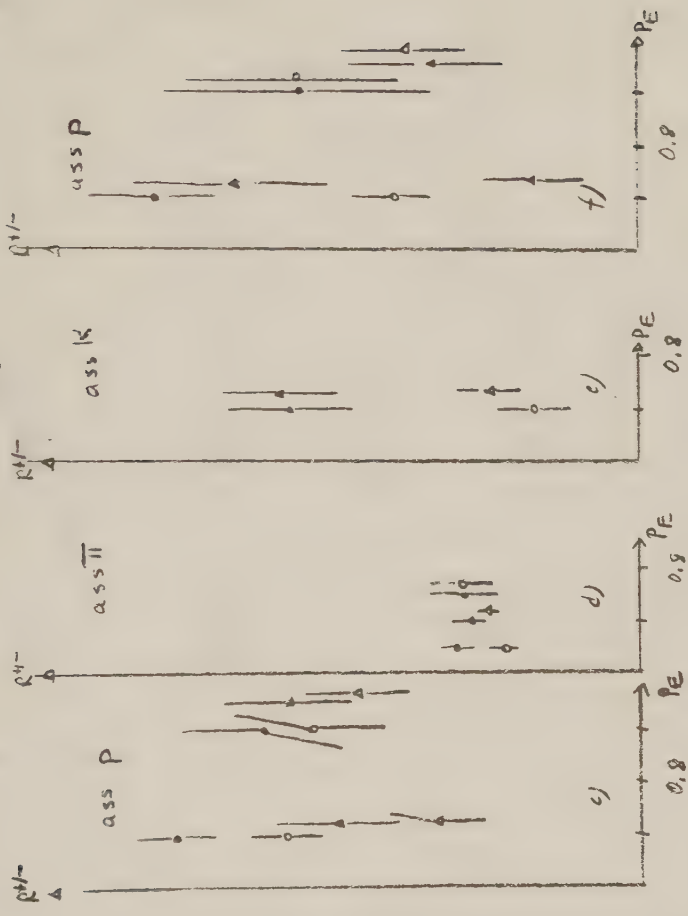


figure 12

$$3 < P_{T \text{ min}} < 4.5 \text{ GeV}/c$$

$$P_T > 1.5 \text{ GeV}/c$$

$$|\Delta\phi| < 30^\circ$$

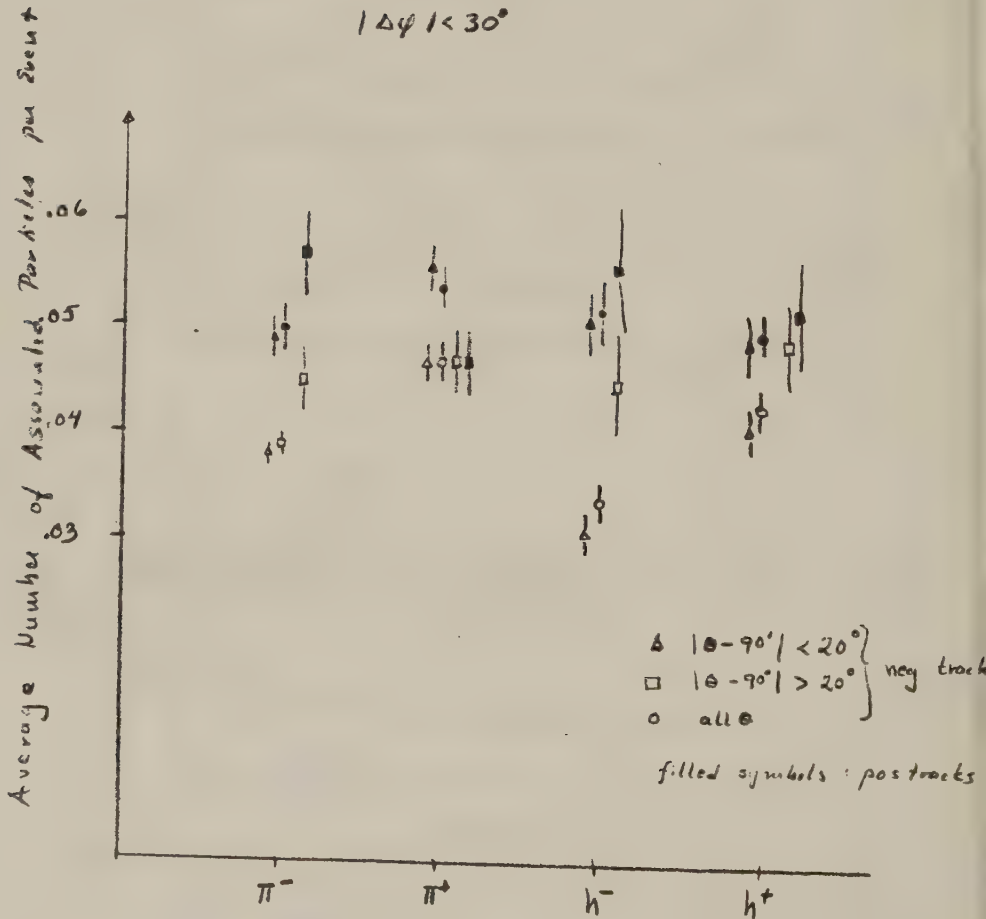
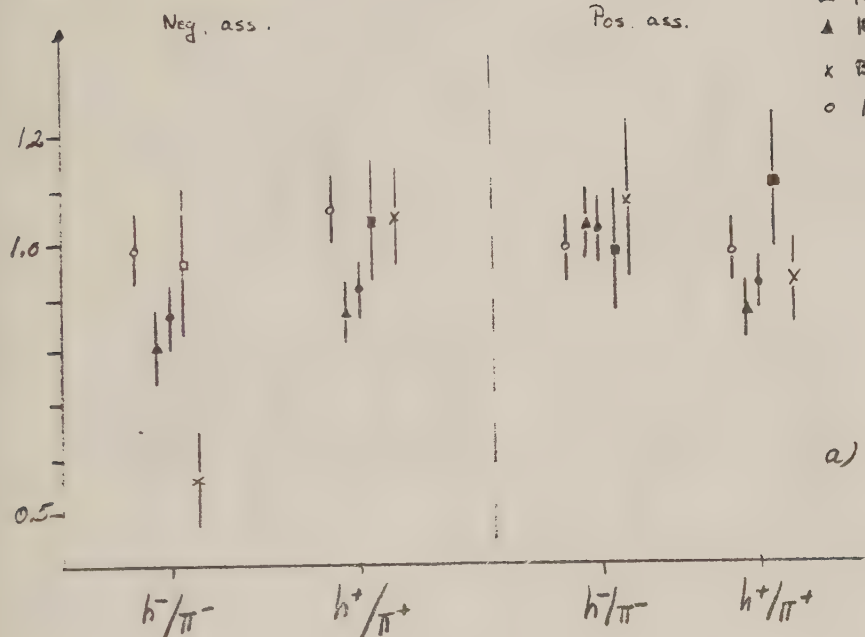


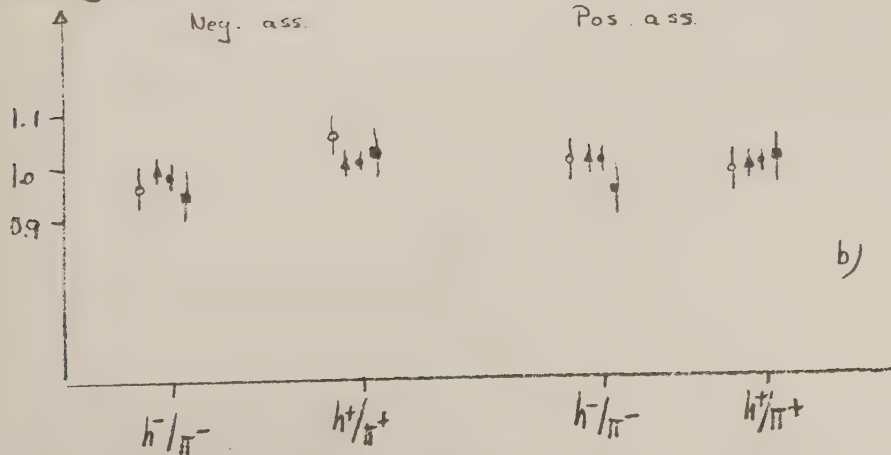
figure 13

Density Ratio



a)

Density ratio



b)

Figure 14

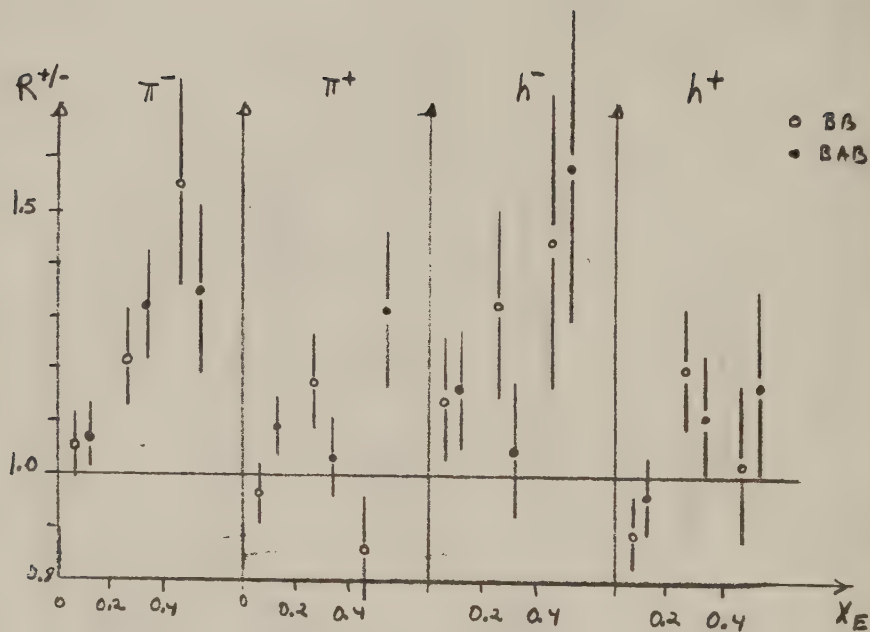


figure 15

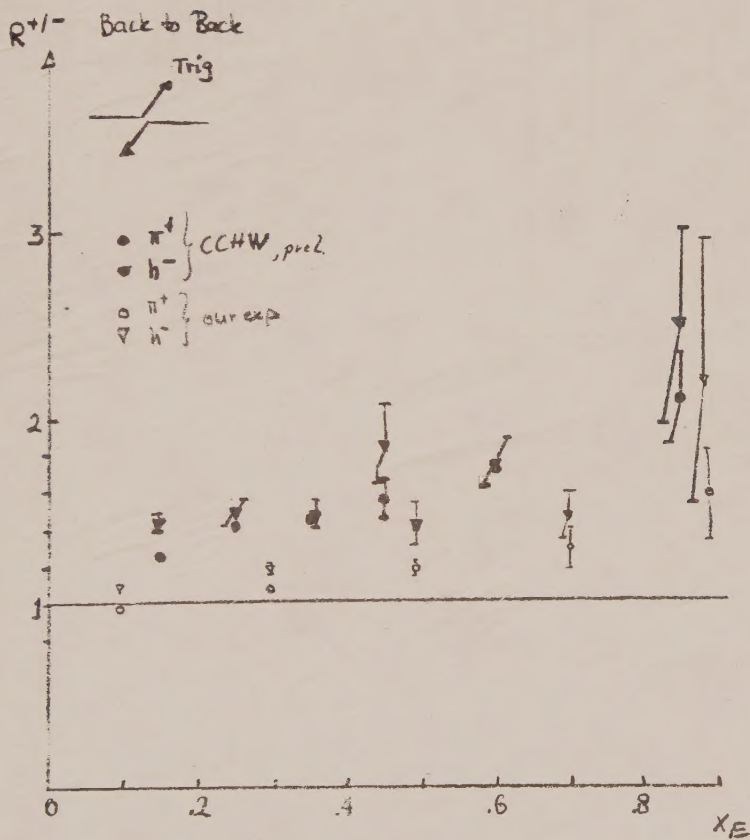


figure 16

